CHAPTER 2

BIOLOGY AND BIOGEOCHEMISTRY OF ECOSYSTEMS AND THE GLOBAL CARBON CYCLE

2.0 INTRODUCTION

Earth's ecosystems are being subjected to human intervention and environmental changes on an unprecedented scale, in both rate and geographical extent. The ability of human societies to ameliorate, adapt to, or benefit from these rapid changes requires fundamental knowledge of the responses of terrestrial and marine ecosystems to global change (IGBP, 1992). Also required is an understanding of the implications of these changes for increased food production, sustainable resource management, and the maintenance of a healthy, productive environment. As human societies seek to develop policies that respond to the impacts of global change, there will be a continuing requirement for objective, scientific information to understand the current impacts and predict the future effects of such policies. Presently, there is an urgent need for information on sources and sinks of carbon in the environment and on the capacity of terrestrial and marine ecosystems to store carbon dioxide released to the atmosphere as a result of human activities.

NASA research on the biology and biogeochemistry of ecosystems and the global carbon cycle aims to understand and predict how terrestrial and marine ecosystems are changing. This research theme addresses ecosystems as they are affected by human activity, as they change due to their own intrinsic biological dynamics, and as they respond to climatic variations and, in turn, affect climate. Emphasis is on understanding the processes of the Earth system that affect its capacity for biological productivity and on the role of the biosphere in Earth system function. Documenting and understanding changes in land cover and land use are priorities. Understanding the distribution and cycling of carbon among the active land, ocean, and atmospheric reservoirs constitutes a major scientific focus for research as well as a new priority for interagency cooperation and international assessment (USGCRP, 1999).

2.1 SCIENCE QUESTIONS

How are global ecosystems changing? (Question V3)

Terrestrial and marine ecosystems are subject to change from natural variability in the environment, their own internal biological dynamics, and changes brought about by human activities. Changes occur in virtually all aspects of the environment, including atmospheric composition, the deposition of nutrients, incident solar radiation, climate, land use and fishing practices, and biodiversity. More subtle, though no less important, changes are occurring in the temperature and circulation of the ocean. Many of these environmental components are not only varying, but are trending or increasing in rate or amplitude of variation. Thus, it is vitally important to be able to discriminate between those variations related to intrinsic dynamics and the variability of the global environment and those that are caused by human actions and which therefore may result in significant changes in the state and future evolution of ecosystems. We will need to document the spatial distribution and extent, temporal dynamics, and productivity of Earth's ecosystems in order to provide a baseline against which to evaluate future change.

What changes are occurring in global land cover and land use, and what are their causes? (Question F2)

Changes in the Earth's land cover and land use are pervasive and increasingly rapid; few landscapes are unaffected. The causes of change in land cover and land use arise from a combination of human (social, economic, policy) and biophysical (biogeochemical, hydrologic, climatic) factors. Changes in land use and land cover resulting from the need to feed an expanding human population will constitute the most important forcing on terrestrial ecosystems over the next several decades (IGBP, 1997). Knowing which landscapes are changing and how they are changing will be important for optimal food production, natural resource management, biological conservation, and carbon monitoring. We will need consistent and reliable information on changes in land cover and land use over periods of years to decades. Quantifying vegetation recovery from past land clearing will be critical for assessing terrestrial carbon sinks. We also will need to understand the causes of land cover and land use change, including both human actions and climatic factors, in order to predict future changes (IGBP/IHDP, 1995).

How do ecosystems respond to and affect global environmental change and the carbon cycle? (Question R2)

The Earth's ecosystems are experiencing widespread disturbance, novel environments, and exploitation by an increasing human population. There are great uncertainties in our understanding of how present-day ecosystems respond, and this makes predicting how they will respond to future changes a major scientific challenge (NRC, 1994). Improved ecological information on the responses of ecosystem distribution, structure, and physiological and biogeochemical function to global environmental change will be essential to meeting this challenge. Changes often occur in interacting combinations, and we need improved understanding of how ecosystem components and functions respond to multiple stresses (NRC, 1999) and disturbances. We can anticipate some environmental changes that may occur in the future, such as altered precipitation patterns or increased frequency of extreme weather events, but others may surprise us. It is vitally important to investigate the implications of such changes for sustained agriculture, forestry, and fisheries, and for the continued provision of ecosystem goods and services that are valuable to human societies. There also are significant uncertainties regarding the responses of ecosystems as they, in turn, feedback to control fluxes of water, energy, and trace gases. Determining the magnitude of these effects will be important for assessing impacts on climate and atmospheric composition (IPCC, 1996).

Carbon is the basic constituent of all biological systems. Along with the oceans and the atmosphere, the biosphere is one of three active global carbon reservoirs. Through the processes of photosynthesis, respiration, and decomposition, marine and terrestrial ecosystems cycle carbon among these reservoirs. Atmospheric carbon dioxide concentrations have been increasing over the past 250 years, This increase is primarily caused by fossil fuel burning and forest clearing, and constitutes the largest anthropogenic contribution to the planetary greenhouse effect and the potential for climate change. Increasing atmospheric carbon dioxide levels also can stimulate photosynthetic carbon fixation in terrestrial plants (an effect often referred to as carbon dioxide fertilization) and may result in increased carbon storage in terrestrial ecosystems. Forest clearing releases carbon to the atmosphere and subsequent regrowth takes up carbon dioxide, but the net effect on regional carbon storage over time is not clear. The oceans also take up carbon dioxide, but the strength of this sink, its evolution over time, and the interaction with the ocean's planktonic ecosystems are equally unclear. Recent studies indicate the global biosphere must be storing significant amounts of anthropogenic carbon dioxide each year, thus, reducing the total amount remaining in the atmosphere, yet we do not know where this carbon is going or how long the storage can persist. We need to understand the past and present roles of ecosystems in storing carbon and to predict their future role under a range of scenarios (Sarmiento, et al., 1999). A complete understanding of the carbon cycle will require knowledge of its interactions with the nitrogen, phosphorus, and sulfur cycles; with other trace nutrients; and with the water cycle.

What are the consequences of land cover and land use change for the sustainability of ecosystems and economic productivity? (Question C2)

Changes in land cover and land use have impacts and implications at local, regional, and global scales because of the way they alter Earth system biophysical, biogeochemical, and hydrological states and processes. These changes affect agricultural, forest, and water resources; biodiversity; carbon storage or release; and the geographic distribution and activities of human populations. We need quantitative information on the consequences of land cover and land use change, including changes in productivity patterns, land degradation, intensified management, and loss of biodiversity; changes in the storage and fluxes of important biogeochemical elements, especially carbon and water; and increased inputs of pollutants, nutrients and sediments to coastal oceans. Future estimates of greenhouse gas emissions, assessments of climate change impacts, and evaluation of land management practices and possible mitigation strategies will depend upon information on the consequences of land cover and land use change. An ability to realistically model ecosystems undergoing land use change will be critical to the success of these endeavors. Ultimately, this research must provide the scientific underpinning for sustainable management of the natural resources of our planet.

What are the consequences of climate and sea level changes and increased human activities on coastal regions? (Question C3)

Coastal regions are extremely vulnerable to severe weather events and sea-level rise, and they are increasingly disturbed by human activities. Land cover and land use changes within the drainage basins of the rivers feeding into coastal regions are major sources of sediments, nutrients, and pollutants to coastal ecosystems. Rapid growth in coastal populations poses additional severe pollution risks. Understanding the consequences of these human activities, in combination with the effects of global climate change and sea-level rise (see also 6.3.4 of Solid Earth chapter), will be needed for effective resource management in the coastal zone and for us to mitigate effectively or adapt to the changing coastal environment.

How well can cycling of carbon through the Earth system be modeled, and how reliable are predicted future atmospheric concentrations of carbon dioxide and methane by these models? (Question P5)

Reliable estimates of future atmospheric concentrations of carbon-containing greenhouse gases are needed to evaluate potential global environmental changes. To be able to predict future atmospheric concentrations of carbon dioxide, we must understand the mechanisms that control the carbon cycle, including how they interact with each other and with the environment. Only by accurately representing carbon cycle processes in models can we hope to produce realistic projections of future atmospheric concentrations. New and improved models must be developed and rigorously tested. We need improved models of ecological and biogeochemical cycling that calculate carbon uptake and emissions based on remote sensing observations and point data from *in situ* networks. We need models to extend these results across landscapes, regions, ocean basins, and the entire Earth system. We need models to simulate scenarios of change over time and that can produce credible predictions. For methane, we also need improved atmospheric chemistry models and to establish linkages between them and ecosystem and biogeochemical cycling models (see also Chapter 3, Atmospheric Chemistry, Aerosols, and Solar Radiation). Current climate models do not incorporate a dynamic understanding of the carbon cycle, and are not able to reproduce patterns of variability in, for example, source and sink regions for carbon dioxide. Advances must be made toward the development and implementation of dynamic, coupled models of the land-atmosphere, ocean-atmosphere, land-ocean, and land-ocean-atmosphere systems to achieve realistic carbon cycle portrayals. These new models also should be capable of evaluating alternative scenarios for management of carbon.

To answer these questions, NASA will pursue a strategy combining remote sensing observations with *in situ* observations, basic research, process studies, and modeling. These activities will focus on integrating and extending knowledge across spatial and temporal scales, and on predicting ecosystem responses to global environmental change. The desired outcomes include:

- scientific assessments of specific ecosystem responses to potential environmental changes and quantitative carbon budgets and emissions estimates of key global ecosystems for decision-making purposes;
- fundamental understanding of primary productivity and the consequences of land cover and land use change as a basis for applications to agriculture, forestry, fisheries, sustainable land and marine resource management, and biodiversity conservation; and
- information on ecosystem interactions with the atmosphere that can be used to improve weather and climate prediction and to assess impacts on atmospheric chemistry.

2.2 NATURE OF THE PROBLEM AND SCOPE OF THE PROGRAM

Planet Earth offers the only opportunity to study living systems and the processes of life. The present Earth system is the result of the coupled evolution of life and the planet. It is the product of interactions among the biosphere, hydrosphere, atmosphere, and geosphere over billions of years. On Earth, the basic chemical constituents of organic matter, carbon, nitrogen, oxygen, phosphorus, and sulfur, follow a closed loop or cycle through increasing energy states, as they are incorporated into living tissue, and then decreasing energy levels as the tissues decompose, giving rise to the biogeochemical cycles. These biogeochemical cycles are an expression of life and the signature of a living planet.

The ecosystems of Planet Earth are an essential foundation for human societies – they are, quite simply, our life support system. People depend on ecosystems for an extensive variety of goods and services. Food, forage, fiber, timber, construction materials, and pharmaceuticals exemplify the goods. Services include the maintenance of water resources, air quality, soil fertility, fisheries, wildlife habitat, and biodiversity. Climate regulation and recreational opportunities are considered other types of services. Healthy ecosystems strengthen economies and make sustained use possible; damaged ecosystems weaken economies and pose severe challenges for continued use.

For the first time in history, the actions of one species – humans – are changing atmospheric composition, climate, hydrology, land cover, and soils at unprecedented rates globally. Population growth, increasing levels of consumption by society, and changes in technology and socio-political organization are responsible for these accelerated environmental impacts (IGBP, 1997). Nearly half the population of the world resides in coastal regions, and the coastal ocean is increasingly disturbed by human activities. Marginal lands with limited soil fertility or water resources are supporting more people. Continued population growth can only increase pressure on the Earth's resources.

Since the beginning of the Industrial Revolution, human activities have significantly altered biogeochemical cycling, and the magnitude of human disturbance may be approaching a critical level: the concentrations of atmospheric carbon dioxide and methane are moving into ranges without historical precedent. Recent policy debates have demonstrated the need to quantify sources and sinks of carbon dioxide and other greenhouse gases on national, regional, and continental scales and to predict how these sources and sinks might change in the future.

Human agricultural, urban, and industrial activities have had similar impacts on the nitrogen, phosphorus, and sulfur cycles. The increased availability of these nutrients is especially important for understanding regional productivity patterns and global carbon stocks. Excess nutrients are reaching and affecting aquatic systems such as groundwater, wetlands, lakes, rivers, estuaries, and the coastal ocean. The global carbon, nitrogen, phosphorus, and sulfur cycles are interlocked, and perturbations in one will have impacts on the others. These perturbations constitute an ongoing biogeochemical experiment at the global level, and raise serious questions for all societies.

Thus, the NASA Earth Science Enterprise (ESE) contribution to the study of life in the universe focuses on understanding change in the Earth's ecosystems and biogeochemical cycles and on predicting future changes and their consequences at time scales relevant to humans. This research addresses major objectives of the U.S. Global Change Research Program's (USGCRP) Biology and Biogeochemistry of Ecosystems program element and its Carbon Cycle Science initiative. It also forms the core of ESE's contribution to NASA's cross-Enterprise program in Astrobiology. Current and future ESE research to address the six science questions identified in section 2.1 targets the following major topic areas: global primary productivity, land cover and land use change, ecosystem responses and feedback processes, and the global carbon cycle.

2.2.1 Global Primary Productivity

Photosynthetic carbon fixation by terrestrial plants and marine algae, referred to as primary productivity, is the basic energy capturing process that fuels nearly all life on Earth. Net primary productivity (NPP) is the measure of productivity left after losses due to plant respiration are subtracted. Roughly half (55%) of global NPP occurs on land, resulting in the storage of carbon in the form of plants, plant litter, and soil organic matter. The remainder (45%) takes place in the oceans, due almost entirely to the life cycle of phytoplankton (single-cell algae) in the upper illuminated layer. As phytoplankton photosynthesize, the partial pressure of carbon dioxide in the surface ocean becomes under-saturated relative to the atmosphere, thus drawing carbon dioxide from the atmosphere into the ocean; this is the so-called "biological pump".

Changes in NPP and its global distribution are of great concern because of the direct consequences for human and animal food supplies. For agriculture, forestry and fisheries, the harvestable fraction of this total NPP (i. e., yield) is the relevant measure of productivity. Both NPP and yield are amenable to estimation using satellite data. For questions of carbon cycle dynamics, net ecosystem productivity (NEP) and net biome productivity (NBP) are the measures needed. NEP is obtained by subtracting from NPP the losses of carbon due to heterotrophic respiration and decomposition processes within the ecosystem. NEP may be either positive or negative and is determined by the balance between photosynthetic uptake (which increases with atmospheric carbon dioxide, although at a diminishing rate) and losses due to respiration and decomposition (which increase at an increasing rate with temperature). NBP is NEP summed across the full spatial extent of a given biome, accounting for landscape heterogeneity.

Factors that can increase NPP include recovery from past disturbances and management practices; favorable changes in climate; and nutrient fertilization resulting from atmospheric deposition, oceanic circulation and upwelling, or agricultural application (nitrogen and phosphorus are most important in terrestrial ecosystems, and nitrogen, iron, and other trace elements are most important in marine ecosystems). Carbon dioxide fertilization, in combination with its effect of increased water use efficiency, can also increase NPP in terrestrial ecosystems, but the net effect on NEP and carbon storage of this direct forcing of carbon dioxide on photosynthesis in combination with its indirect forcing through increasing temperature on respiration and decomposition is not well-understood. Factors that can decrease NPP include nutrient limitations, the dissemination of toxic pollutants, urban encroachment on arable lands, poor management practices, and unfavorable climatic changes.

2.2.2 Land Cover and Land Use Change

Distribution and Extent of Land Cover and Land Use Change

Today, a consistent, global-scale database of land cover and/or land use change over the last 200 years does not exist. This period is particularly important because the global population increased ten-fold, population density in several regions increased by more than 100 times, and agriculture replaced natural vegetation in large parts of North America, China, and India. Even more surprising, perhaps, is that there is no consistent, high resolution, global land cover time series data product for the past 20 years of satellite remote sensing. Progress in understanding how humans are changing the Earth is partially stymied by this lack of consistent information on land cover and land use change. There is a strong need to mine the existing record of high resolution satellite imagery to provide a baseline of land cover change and its impacts, and to ensure that these changes are more consistently documented and assessed in the future.

Causes of Land Cover and Land Use Change

To understand the consequences of land cover and land use change, both the biophysical and the human factors that cause land cover and land use changes must be addressed. The demand for food to feed an increasing world population will force further conversion of natural ecosystems to agriculture and the intensification of production on currently cropped lands. Other changes in land cover are expected to occur due to changes in forest exploitation, and, possibly, due to afforestation measures attempting to sequester carbon from the atmosphere. Natural and human-induced disturbances such as fire, insect infestations, and logging change large areas of the Earth's surface, but more subtle changes that result in habitat degradation and fragmentation are also important because they lead to diminished ecosystem functionality and loss of biodiversity.

Consequences of Land Cover and Land Use Change

Quantifying the impacts of land cover and land use change on carbon sources and sinks will be critical to understanding the overall response of the carbon cycle to human activities. One of the main driving factors responsible for current carbon uptake on land may be land use, both past and present. Widespread reforestation of agricultural lands, as has been occurring since 1900 in the eastern U.S., and increased productivity on remaining agricultural lands has led to increased carbon storage in forests and soils. On the other hand, clearing of forests for agriculture in other parts of the world, for example in tropical forest regions, is releasing carbon to the atmosphere. We need accurate estimates of the regional and global effects of historical and current land use change and land management practices on carbon sources and sinks.

Land cover and land use change constitute the primary contributor to the loss of biodiversity at all levels (genes, species, and ecosystems). Human-introduced invasive species and pathogens are also changing the biodiversity of the planet. The majority of the Earth's species reside in the humid tropics, and these species-rich areas are undergoing the most rapid rates of human population growth accompanied by economic development -- two factors that have traditionally led to the rapid conversion and loss of natural land cover. While land cover can on occasion be restored, a lost species and its unique genotype and role in an ecosystem are lost forever. In order to understand the true nature and extent of ongoing biodiversity loss, information is needed on the rate and magnitude of conversion of natural land cover at local to global scales.

Changes in land use will result in increasing stress on riverine and coastal ecosystems. Near-shore embayments, estuaries and wetlands are the spawning and nursery grounds for many fish species. Coastal regions are susceptible to over-fertilization by nutrient-rich river discharge and atmospheric deposition, with consequent depletion of oxygen (hypoxia) and widespread fish mortality. Increases in phytoplankton concentrations or sediment loads pose a threat to coral reef ecosystems, which thrive only in very clear tropical waters.

2.2.3 Ecosystem Responses and Feedback Processes

Ecosystem Responses to Environmental Change

Ecosystem responses to environmental change can occur on a wide range of time scales and may involve changes in physiological or biogeochemical functions, and/or changes in distribution and structure (e. g., species composition, biomass distribution, canopy architecture). Forcings of change can be broadly categorized as stresses, which are often chronic in nature, and physical disturbances, which tend to be episodic.

Physiological processes will dominate short-term responses to change. They control the accumulation or loss of biomass, the cycling and storage of key nutrients, and the exchanges of energy, water, and trace gases with the atmosphere. In terrestrial ecosystems, these processes are affected in a complex, interactive way by forcings from changes in atmospheric carbon dioxide, land use practices, temperature, rainfall, and incident solar radiation. A principal objective is to acquire quantitative information about canopy and land surface biophysical or biochemical properties that characterize important physiological processes. This information is needed to drive ecological models and has proven to be indispensable in scaling them up for regional and global applications as well as in scaling down global models. In marine ecosystems, phytoplankton population turnover rates are governed by changes in the supply of light and nutrients, and can be as short as 1-2 days. Wind mixing and vertical stratification of the upper ocean, thermohaline (density-driven) circulation, nutrient deposition by rainfall and dust, and cloudiness are some of the forcing factors. Carbon dioxide is not a limiting factor in the ocean.

On longer time scales, changes in the composition and structure of both terrestrial and marine ecosystems will dominate. Such changes may include changes in the geographic distribution and extent of terrestrial and ocean ecosystems, as well as changes in the species composition of their communities. We know that ecosystems are not necessarily in equilibrium with their physical and chemical environment, that stress response thresholds exist, and that abrupt transitions from one type of ecosystem to another are possible. Better representation of the relevant processes and forcing factors is needed for the next generation of ecosystem models in order to capture the nature of these transitions and predict future responses. Observations to track both the occurrence of and the recovery from major disturbances (e.g. fire, introduction of invasive species, insect infestations, deforestation) are critical for understanding terrestrial ecosystems. Moreover, chronic stresses (e.g., grazing, nitrogen deposition) that cause slower changes in structural and biogeochemical dynamics will require observations of variability and trends over periods of many years.

We have yet to understand shifts in ecosystem structure and function that have been known to occur rapidly and persist for decades, with significant impacts on biogeochemical cycling and the availability of food and other natural resources. Ecosystem responses may have lag times of decades or longer or they may occur only when certain critical thresholds are exceeded. Such phenomena, if not accounted for in predictions, have the potential to cause surprises for which human societies are unprepared. More realistic ecosystem models are needed to handle such effects.

Ecosystem Feedback to Atmospheric Chemistry and Climate

Ecosystems play a significant role in modifying the atmosphere. They are sources and sinks of trace gases, including the greenhouse gases that control climate. Methane is of particular concern because the cause(s) for its recent increase in concentration in the atmosphere are not identified (i. e., known sources and sinks do not balance the global methane budget), nor do we understand the interannual variations in atmospheric methane concentrations. Fires, which occur due to natural climate-related causes as well as human actions, release to the atmosphere large pulses of carbon dioxide and other trace gases, as well as extensive amounts of soot and carbonaceous aerosols. Biogenic sources of nitrous oxide, a greenhouse gas, and methyl bromide, both of which play a role in stratospheric ozone depletion, are significant.

Terrestrial vegetation directly influences the global water cycle and also affects atmospheric circulation through changes in evapotranspiration, surface albedo, and roughness and, consequently, surface temperature, the stability of the atmospheric boundary layer, precipitation, and weather. Many ecosystems recover from disturbance or environmental stress slowly and retain a memory of the past stressful conditions, thereby introducing significant time lags in ecosystem response to climate variability and in subsequent feedback to the climate system. Changes in land cover and land use can result in large changes to surface properties. The amount of forcing these changes can exert on the total Earth system is currently not known. Sensitivity studies with altered land cover distributions in general circulation models have shown that drastic changes in land cover may lead to significant feedbacks to atmospheric circulation. In addition, regional climate simulations have shown that important teleconnections may exist whereby changes in one region may cause a change in climate conditions in other, less disturbed areas.

Rapid feedback to the climate system is possible in ocean ecosystems because phytoplankton populations turn over quickly. One potential feedback mechanism between oceanic biological productivity and climate involves the effect of precursor compounds (e.g., dimethyl-sulfide and dimethyl-sulfonium propionate) produced by oceanic phytoplankton that generate sulfur-based aerosols. These aerosols act as cloud condensation nuclei and the resulting clouds reduce the transmission of photosynthetically active radiation and increase planetary albedo, thus introducing a negative feedback to biological productivity and a cooling effect on climate.

2.2.4 The Global Carbon Cycle

Estimates of the net anthropogenic carbon budget for 1980-1989 are shown in Table 2-1. The annual mean carbon budget requires an inferred sink to balance known sources, but the exact nature of the sink(s) is not known. The latitudinal distribution of sources and constraints on inter-hemispheric transport of carbon dioxide point to the existence of two sinks. The larger sink is in the Northern Hemisphere (where the largest sources are located) and thought to be in terrestrial ecosystems; a smaller sink, likely associated with oceanic biogeochemical processes, is thought to exist in the Southern Ocean (Sarmiento et al., 1999). The sources and sinks with greatest relative uncertainty in Table 2-1 are associated with land use and land cover change, and oceanic uptake. The oceans are, without question, a net sink for anthropogenic carbon dioxide, but the strength of this sink is unclear, and the sensitivity of the biological pump to environmental change is not well-understood. In terrestrial ecosystems, forest clearing is a source of carbon to the atmosphere, but subsequent secondary regrowth of natural vegetation after clearing due to fire or abandonment of agricultural lands can result in rapid uptake of carbon dioxide; the net carbon balance of such recovering ecosystems, especially over a full successional cycle, is not well-understood. More subtle, are uncertainties related to the possible changes in carbon storage resulting from carbon dioxide fertilization of terrestrial ecosystems, changes in other global biogeochemical cycles, and/or changes in the physical climate system. Understanding the global carbon cycle will be key to comprehending ecosystem change and to developing a reasonable range of scenarios of future atmospheric concentrations of carbon dioxide and other greenhouse gases for use in Earth system models.

The international Framework Convention on Climate Change calls for limitation of the annual net emissions of six greenhouses gases, including carbon dioxide, by the years 2008-2012. Significant sinks such as reforestation may be accounted for as negative emissions to offset sources. Thus, many nations are beginning to consider how best to develop national inventories of carbon emissions and to evaluate enhanced carbon storage in their ecosystems. Considerably improved measurements of fluxes and better understanding of natural sources and sinks will be required for a nation to conduct such carbon accounting, let alone adhere to any agreed-upon protocols. The possibility for ecosystems to absorb significant amounts of carbon dioxide, thus slowing the accumulation of carbon dioxide in the atmosphere, is a key issue in the debate on carbon dioxide emission controls. If terrestrial ecosystems can be managed for this purpose, it becomes imperative to learn how long this capability can be maintained and whether it can be increased. There is also growing interest in iron fertilization of marine productivity as a method of stimulating carbon sequestration. Recent experiments in the Equatorial Pacific and the Southern Ocean confirm the effect, but more research is needed to understand the ecological consequences and effectiveness of the approach.

TABLE 2-1

Anthropogenic Carbon Budget for 1980-89 (IPCC, 1995)
(Units are GtC/yr; uncertainties are 95% Confidence Limits)

Carbon Dioxide Sources		
(1)	Emissions from fossil fuel combustion and cement production:	5.5 ± 0.5
(2)	Net emissions from changes in tropical land use:	1.6 ± 1.0
(3)	Total anthropogenic emissions [(1)+(2)]:	7.1 ± 1.1
Partitioning Among Reservoirs		
(4)	Storage in the atmosphere:	3.3 ± 0.2
(5)	Ocean uptake:	2.0 ± 0.8
(6)	Uptake by Northern Hemisphere forest regrowth:	0.5 ± 0.5
(7)	Inferred sink [(3)- {(4)+(5)+(6)}]:	1.3 ± 1.5

2.2.5 Strategy and Program Plan for Biology and Biogeochemistry of Ecosystems and the Global Carbon Cycle Theme

Overall Strategy

NASA ESE research on the biology and biogeochemistry of ecosystems and the global carbon cycle requires a coordinated national and international effort to acquire global data sets and assess the effects of global environmental change. NASA's contribution is focused on providing data and information derived from space-based remote sensing systems capable of observing the Earth's ecosystems at multiple scales and across the full range of the electromagnetic spectrum. Both moderate and high spatial resolutions and frequent repeat observations are required. Airborne and *in situ* observations, intensive field campaigns, process studies, data and information systems, and models are equally important to NASA's contribution because they are absolutely essential for interpreting and making full use of satellite observations. The strategy is to realize an optimal balance among systematic and exploratory measurements from space, airborne and *in situ* observations, basic process studies, case studies, modeling, and integrative data analysis. It is to be expected that this balance will change as scientific understanding and technological capabilities evolve and as space missions advance from the conceptual stage through flight and data analysis.

Priorities for Satellite Missions

The post-2002 mission planning process assigned high priority to the systematic observations that will fulfill the need for continuous records of biospheric state and activity to address questions of decadal-scale variation in ecosystems. Measurements of ocean color, terrestrial vegetation biophysical properties, and land cover provide the critical foundation for addressing all of the science questions highlighted in this chapter. They support research on natural variability of the biosphere, forcings of the Earth system by land cover change, response of ecosystems to changes, and assessment of consequences for human societies. These data sets also are needed as critical inputs for ecological, biogeochemical, and land cover change models, including those that predict future changes to the Earth system. The major challenge for NASA is to ensure that these global measurements continue in such a way as to promote scientific continuity, while encouraging the evolution of instrument and other mission technologies at reasonable costs.

For the foreseeable future, mission concepts that offer the most significant advances toward understanding and quantifying global carbon cycle dynamics, including the distribution and composition of land cover, will receive the highest priority. Mission concepts that address impacts caused by disturbance and anthropogenic stresses on marine and terrestrial ecosystems and on their sustainability will receive next highest priority. Proposed exploratory missions are described in the section on program elements (section 2.3). Other ideas for exploratory missions will, no doubt, arise as both scientific understanding and technological capability advance. Investments in basic preparatory science and technology development will be made to advance the most promising concepts, and then decisions as to which mission(s) to pursue will be made at an appropriate time based on peer review and with due consideration of other scientific, programmatic, national, and international priorities (see section 1.3, Overview). Commitments to the pursuit of a new type of exploratory science mission will be made only after the technology has been evaluated and the new measurement capability has been assessed for scientific validity and the potential to answer a critical global change question.

Planning for Field Campaigns and Modeling

The development and approval processes for space-flight missions necessitate a detailed strategic plan of specific missions that will be scientifically compelling and technologically feasible in a 5-10 year time frame. However, flexibility is paramount for planning future field campaigns and process studies as well as for deciding upon the next steps in modeling and integration. It is not uncommon for scientific priorities to shift as breakthroughs occur and attention to turn rapidly from reducing one major scientific uncertainty to addressing the next. Field campaigns and process studies can have maximum impact by responding to these advances, and, therefore, benefit from a flexible and near-term planning and commitment process within the context of an on-going research and analysis program. The same is true for identifying the next steps in modeling. Thus, these components of the implementation plan for biology and biogeochemistry of ecosystems and the global carbon cycle do not have rigidly defined plans for the period after 2005.

The process for identifying future science-driven field campaigns requires a dialogue within the ESE research community that leads to a scientific consensus on the priority problem or problems to target. ESE priorities, logistical and cost considerations, and national and international partnerships are then factored into NASA's decision as to which field campaign to pursue. Consultation and coordination with other national and international research sponsors throughout the planning and implementation process is essential. Interactions with IGBP's core projects are particularly valuable. Inclusion of scientists from the region of a field campaign has clear benefits and is expected. Definition of satellite validation-driven field campaigns is usually conducted by the satellite instrument science team or by a validation science team selected through a separate competitive process. In the future, field campaigns that strongly integrate science and satellite validation objectives will receive priority.

Essential Interactions

The scientific research agenda for NASA research on the biology and biogeochemistry of ecosystems and the global carbon cycle is heavily influenced by the scientific recommendations, plans, and initiatives of the U.S. National Academy of Science, the U.S. Committee on Environment and Natural Resources (CENR), and the International Geosphere-Biosphere Programme (IGBP). The CENR Subcommittee on Global Change Research (USGCRP) provides the primary forum for setting scientific priorities and coordinating research and scientific assessment activities with other U.S. agencies, but there is also interaction with the CENR Subcommittee on Ecological Systems. Opportunities to collaborate with other space agencies also influence this research agenda.

Research on the biology and biogeochemistry of ecosystems and the global carbon cycle is closely intertwined with that of the other research themes within the ESE, especially given the importance of cross-disciplinary research for advancing Earth system models – which are the common tools needed to predict future global changes and their consequences for societies. In addition, there is a strong linkage to ESE Applications programs, with emphasis on extending understanding of global productivity patterns to agricultural, forestry, and fisheries applications; developing the scientific basis for new applications of satellite data; supporting national and international environmental vulnerability assessments; and addressing the consequences of ecosystem disturbances from such natural hazards as fire, flooding, oil spills, and extreme weather.

This research agenda intersects with that of NASA’s cross-Enterprise research program in Astrobiology. ESE leads research efforts aimed at the Astrobiology goal of: "determining how ecosystems respond to environmental change on time scales relevant to human life on Earth.” Research within the biology and biogeochemistry of ecosystems and the global carbon cycle theme also supports other Astrobiology goals through (1) research on microbiology (related to controls on nutrient cycling and trace gas emissions), (2) development of Earth system models that simulate the co-evolution and adaptation of life and the changing environment, and (3) research to characterize the signals of life that can be remotely sensed for Earth.

Overall Program Plan

Systematic Observations

Understanding how ecosystems vary over time (Question V3), respond to global environmental change (Question R2), and affect the global carbon cycle (Question R2) requires consistent time series of satellite observations of global ocean color, vegetation properties, and land cover. The Sea-viewing Wide Field-of-view Sensor (SeaWiFS), the Moderate-Resolution Imaging Spectro-radiometer (MODIS) of the Earth Observing System (EOS), the Global Productivity Mission, and the Sensor Intercomparison and Merger for Biological and Interdisciplinary Ocean Studies (SIMBIOS) project (see Ocean Ecology and Biogeochemistry (OEB) program element, section 2.3.1.1) fulfill the need for ocean color data to produce estimates of ocean primary productivity and to drive models of ocean carbon dynamics. The Advanced Very High Resolution Radiometer (AVHRR), MODIS, and the Global Productivity Mission (see Terrestrial Ecology and Biogeochemistry (TEB) program element, section 2.3.2.1) fulfill the need for moderate spatial resolution vegetation indices and biophysical properties to produce estimates of terrestrial primary productivity and to drive models of terrestrial carbon dynamics.

Understanding how land cover and land use are changing and also identifying causes and consequences (Questions F2 and C2) primarily require the consistent time series of high spatial resolution satellite observations of global land cover provided by the Landsat 7 and Land Cover Inventory Mission (see Land Cover and Land Use Change (LCLUC) program element, section 2.3.3.1). Additionally, AVHRR, SeaWiFS, EOS, and the Global Productivity Mission (see OEB and TEB program elements, sections 2.3.1.1 and 2.3.2.1) provide useful moderate spatial resolution information on global land cover and on the consequences of land cover and land use change. Landsat 7 and the Land Cover Inventory Mission also provide the needed high spatial resolution land cover and coastal data to assess local to regional scale carbon storage and fluxes and to drive local- to landscape-scale process models of carbon dynamics (Question R2). These systematic missions and measurements are discussed more fully in section 2.3.

Exploratory Observations

There is a strong need for exploratory satellite remote sensing estimates of above-ground biomass (i.e., terrestrial carbon stocks) and information on vegetation response and biomass recovery following disturbance which will be addressed by the Vegetation Canopy Lidar (VCL) mission and the proposed Vegetation Recovery Mission, respectively (see TEB, section 2.3.2.2). These data are needed to reduce uncertainties related to carbon storage in regrowing vegetation (Question R2) and to investigate the consequences of land cover and land use changes caused by disturbance (Question C2). A Cold Climate Land Surface Processes research mission may provide accurate estimates of growing season length and the timing of the spring thaw at high latitudes in order to improve estimates of annual carbon uptake for those regions (Question R2). If sufficiently precise measurements of atmospheric carbon dioxide concentrations could be made from space, such observations would be of high priority for quantifying global sources and sinks of carbon (Question R2) and predicting future atmospheric carbon dioxide concentrations (Question C3; see TEB, section 2.3.2.2). These proposed future exploratory missions and measurements are discussed more fully in section 2.3.

In situ Observations and Process Studies

Field campaigns, *in situ* observations, case studies, and process studies will be conducted (1) to investigate comprehensively ecosystem responses to multiple stressors and disturbances (Questions F2, C2, R2, P5, and C3), (2) to investigate in detail the forcings and consequences of land cover and land use change in the regions of the world experiencing the most change or where anthropogenic stresses are likely to increase most rapidly (Questions F2, C2, and C3), and (3) to understand better the controls on carbon uptake and release by global ecosystems, to understand the effects of interrelated changes in nitrogen, phosphorus, iron and other trace nutrients, and to improve local, national, and regional carbon budget and emissions estimates (Questions R2 and P5).

Modeling

Research to improve ecological, biogeochemical, carbon budget, and land use models will be a priority, as will be research to develop a next generation of coupled land-atmosphere, ocean-atmosphere, land-ocean, and, ultimately, land-ocean-atmosphere models.

Expected Scientific Achievements

In the next decade, the NASA ESE expects to contribute substantially to our understanding of the biology and biogeochemistry of ecosystems and the global carbon cycle and the practical implications of changes in these systems and processes for human societies. NASA ESE research on the global carbon cycle will be fully integrated into the USGCRP's new Carbon Cycle Science program where NASA expects to play a leadership role in providing global satellite observations of carbon sources and sinks, estimating global primary productivity, and developing new space-based measurement capabilities. The satellite observations, field campaigns, case studies, process studies, and modeling activities detailed in section 2.3 have been planned to produce the scientific achievements summarized in Table 2-2.

TABLE 2-2

Expected Scientific Achievements

Question V3: How are global ecosystems changing?

Expected new knowledge in the next 5 years

- Year-to-year variations in global marine primary productivity quantified;
- Year-to-year variations in global terrestrial primary productivity quantified.

Expected new knowledge in the next 10 years

- Decadal variability in ocean primary productivity;
- Relationship between year-to-year variations in net primary production and agricultural and forest productivity at regional scales.

Question F2: What changes are occurring in global land cover and land use, and what are their causes?

Expected new knowledge in the next 5 years

- First quantitative inventory of global forest cover based on Landsat data;
- Global inventory of land cover and analysis of land cover change based on Landsat data, establishing a basis for periodic assessments of global land cover change;
- First ecological, biogeochemical cycling, and land use model simulation results incorporating actual land cover observations;
- Global inventory of fire occurrence.

Expected new knowledge in the next 10 years

- Quantitative assessments of global land cover change on 5 year periods;
- Predictive, coupled socio-economic and ecological models of land cover and land use change;

Question R2: How do ecosystems respond to and affect global environmental change and the carbon cycle?

Expected new knowledge in the next 5 years

- First global estimates of carbon stocks in forests derived from satellite data;
- Quantitative evaluation of coupled land-ocean-atmosphere carbon cycling models;
- Estimation of the efficiency of photosynthetic carbon uptake in marine ecosystems globally;
- First estimates of vegetation height distribution and vertical structure from a space-based lidar sensor, and evaluation of derived estimates of above-ground biomass in forests.
- Process-level and system-level understanding of the effects of deforestation and agricultural use on tropical ecosystems and the implications for sustainable use of Amazonian ecosystems;
- Fully interactive ecosystem-climate models for simulations to evaluate climate change scenarios;
- Ability to identify phytoplankton groups from satellite imagery;
- Analysis of regional trace gas and aerosol emissions from fire.

Expected new knowledge in the next 10 years

- Prediction of the magnitude of carbon export to the deep ocean, and assessment of its sensitivity to environmental factors;
- First quantitative, globally consistent estimate of the rate and amount of carbon uptake in ecosystems responding to disturbance (i.e., secondary forest growth, re-forestation, recovery from stress or catastrophic events);
- Credible estimates of annual carbon uptake and storage in key land regions of the Northern Hemisphere.

Question C2: What are the consequences of land cover and land use change for the sustainability of ecosystems and economic productivity?

Expected new knowledge in the next 5 years

- Evaluation of the utility of remote sensing imagery for assessing the impacts of land cover and land use change on biodiversity.

Expected new knowledge in the next 10 years

- Regional assessments of the consequences of land use change and a first global synthesis;

Question C3: What are the consequences of climate and sea level changes and increased human activities on coastal regions?

Expected new knowledge in the next 5 years

- An accurate map of the extent of coral reefs in the global ocean;
- Discrimination of phytoplankton from detrital material in the coastal ocean;
- Establishment of relationships between ocean processes and fish populations in coastal upwelling regimes.

Expected new knowledge in the next 10 years

- First predictions of the occurrence of harmful algal blooms in coastal waters;
- Quantitative estimates of the exchanges of materials between the land and the coastal ocean.
- Quantitative estimation of coral reef structure from airborne or space platforms

Question P5: How well can cycling of carbon through the Earth system be modeled, and how reliable are predicted future atmospheric concentrations of carbon dioxide and methane by these models?

Expected new knowledge in the next 5 years

- Coupled land-atmosphere model predictions of carbon dioxide fluxes from terrestrial ecosystems.

Expected new knowledge in the next 10 years

- Coupled land-ocean-atmosphere model predictions of carbon dioxide fluxes and concentrations in the atmosphere;
- Coupled land-atmosphere model predictions of methane fluxes from terrestrial ecosystems, including wetlands.

2.3 NASA PROGRAM ELEMENTS

The Earth Science Enterprise (ESE) program elements under the theme of Biology and Biogeochemistry of Ecosystems and the Global Carbon Cycle are:

- Ocean Ecology and Biogeochemistry (OEB);
- Terrestrial Ecology and Biogeochemistry (TEB); and
- Land Cover and Land Use Change (LCLUC).

Each includes:

- Systematic Global Observations;
- Exploratory Satellite Observations;
- Field Campaigns and Process Studies; and
- Modeling and Integration.

These program elements encompass ESE scientific research and analysis programs and major NASA investments in the EOS Terra, EOS Aqua, and Landsat 7 missions; the Earth System Science Pathfinder (ESSP) Program; the New Millennium Program (NMP); and the Instrument Incubator Program (IIP); advanced data and information systems, such as the EOS Data and Information System (EOSDIS), the Earth Science Information Partners (ESIP) federation experiment, and the New Data and Information System and Services (NewDISS); and commercial data purchases.

2.3.1 OCEAN ECOLOGY AND BIOGEOCHEMISTRY (OEB)

The goal of NASA research in ocean ecology and biogeochemistry is to understand the physical and biological controls on primary productivity in the ocean, and to predict how marine ecosystems will respond to, and affect, environmental change.

This program element addresses the variability of marine ecosystems (Question V3), their role in the global carbon cycle (Question R2), and their responses to and effects on global environmental change (Question R2). The consequences of land cover and land use change in the coastal ocean (Questions C2 and C3) are also addressed.

The primary approach is comprised of:

- acquisition of a multi-year global ocean productivity database;
- studies of relevant biological, chemical, and physical processes; and
- development of both process-resolving and global ecosystem models.

Within the above approach, NASA's program in Ocean Ecology and Biogeochemistry has several objectives to be accomplished over the next 10 years:

- assembly of a long-term time-series of ocean color;
- identification of taxonomic groups of phytoplankton from space;
- discrimination of the absorbing and scattering components in coastal water;
- understanding the biological dynamics of the coastal ocean; and
- measuring the depth variability of biological properties of the upper ocean.

Satellite measurements of ocean color are the only source of global information on ocean primary productivity and its response to a variety of factors. The experimental Coastal Zone Color Scanner (CZCS) instrument on Nimbus-7 (1978-1986) first demonstrated quantitative estimation of the concentration of chlorophyll, which can be used as an index of phytoplankton biomass. The chlorophyll measurement is related in a complex way to primary productivity in the surface ocean.

Time-Series of Ocean Color and Natural Variability

While the physical and biological controls on primary productivity are generally understood qualitatively, it remains a problem to quantify and model natural variability in marine ecosystems. It is even more challenging to model these complex physical-biological processes in order to predict the consequences of environmental change. Large-scale transient climate anomalies such as El Niño are, in effect, natural experiments that provide the opportunity to develop and test such predictive biological-physical models. To develop and test models of the biological responses to changes occurring over long time periods requires sustained systematic global measurements of ocean color, together with contemporaneous satellite measurements of relevant physical parameters, including wind stress, ocean dynamic height, and sea surface temperature (see Chapter 5, Ocean and Ice in the Earth System). The acquisition of time series of measurements of ocean color, and therefore, ocean productivity, over decadal time scales, is the fundamental step in understanding the response of ocean ecosystems to global climate change.

Oceanic Forcing

Ocean biological processes cannot be understood without considering the physical processes acting on them. Progress toward understanding global ocean productivity, as revealed by the time series of ocean color measurements, is critically dependent upon contemporaneous global observations of physical variables and processes. This calls for the continuation of systematic satellite observations of dynamic topography (ocean circulation), sea-surface temperature, surface winds, and incident solar radiation, as well as the development of new capabilities such as remote sensing of surface salinity (see section 5.3.1). Emerging areas of interdisciplinary research in remote sensing that NASA will exploit involve the use of ocean color variability to indicate physical phenomena, such as circulation and upwelling, and the use of dynamic topography and winds to estimate productivity.

Responses of Phytoplankton Taxonomic Groups

Recent research indicates that carbon cycling within the euphotic layer depends upon plankton community structure. Where the community is comprised of very small phytoplankton, the phytoplankton are immediately grazed by zooplankton, and organic matter is recycled rapidly, with very little carbon sinking to the deep ocean. Export of organic carbon occurs instead following the seasonal and episodic blooms of larger phytoplankton such as diatoms. Thus, a key to understanding carbon cycling in the ocean is to know what controls blooms. Other functional phytoplankton groups play specific roles, such as the production of calcium carbonate or the fixation of nitrogen. Identifying the factors that control the distribution of such key phytoplankton groups is a central scientific goal. The role of functional groups in biogeochemical cycling, and their responses to different climatic and anthropogenic forcings, can be evaluated with coupled biological-physical models. To provide an observational basis for testing these models, methods will be established for identifying major functional groups from space.

The relationship of planktonic ecosystems to the biogeochemistry of the upper ocean and to atmospheric phenomena is another area targeted for future ESE research. Much of the equatorial and northern Pacific Ocean and the Southern Ocean have low chlorophyll levels throughout the year despite ample supplies of the major nutrients (e.g., nitrate and phosphate). It is believed that iron is the critical missing element in these so-called "high nutrient, low chlorophyll" (HNLC) regions. Even in regions of high chlorophyll content, such as coastal upwelling areas, iron or other micronutrients may ultimately limit productivity. Dust particles carried by winds from African, South American, and Asian deserts are thought to be significant sources of iron for the open ocean. HNLC regions do not currently receive iron from these sources, but changes in atmospheric circulation or desertification might alter the transport of mineral dust with major consequences for oceanic productivity. Experimental additions of iron to the ocean show that the effects are on the larger phytoplankton. Thus, this biogeochemical process affects community structure and, therefore, the ocean's carbon cycling. Other oceanic regions are limited by the availability of fixed nitrogen, supplied by the atmosphere and rivers. Human activities have increased atmospheric nitrogen deposition by as much as a factor of two, and this flux is likely to increase in the future.

Consequences in the Coastal Ocean

. Coastal waters and continental shelves are the most productive areas in the ocean. They support major industries (fisheries, tourism, oil and gas) and constitute the Exclusive Economic Zone (EEZ) which legally extends national boundaries 200 nautical miles seaward. It is estimated that nearly 70% of the U.S. population will live in coastal counties by the year 2020 and similar trends are projected for the world's population. Rapid growth in coastal populations carries severe pollution risks, and calls for effective resource management. Indeed, increased attention is already being paid to phenomena such as harmful algal blooms (WHOI, 1995), coastal and estuarine eutrophication, sea level rise, tsunamis, and hurricanes, all of which have accentuated impacts in coastal zones. For NASA, the major issues in the coastal zone are (1) interpreting satellite imagery for Case-2 waters (i.e., waters containing significant amounts of terrigenous and other non-living material that affects their color) and (2) understanding the dynamics of the coastal ocean. Retrieval of the chlorophyll signal in the presence of the other absorbing substances in Case-2 waters is a current research challenge. Creation of a chlorophyll algorithm for satellite imagery of the coastal ocean will be the first step toward understanding the biological dynamics of the coastal zone. Addressing these issues will enable research applications on fisheries problems, eutrophication, the destruction of coral reefs, and the occurrence of nuisance and harmful algal blooms. Harmful algal blooms also come under the category of natural hazards, in that they affect fisheries, human health, and recreational uses of the coastal zone. This demonstrates a linkage to the ESE Applications Program’s natural hazards research.

Depth Variability of Biological Variables

Satellite imagery shows the spatial variability of biological and physical properties of the ocean, but satellites miss an important component of ocean variability: that is, variation with depth. The ocean's mixed layer depth is a critical factor in the evolution of both physical and biological properties, and therefore important to evaluation of remotely sensed data. For much of the ocean, chlorophyll exhibits strong vertical structure, characterized by a maximum at some distance below the surface. By delineating the vertical distribution of planktonic ecosystems, predictive models of the ocean's carbon cycle will become more accurate. NASA will investigate the feasibility of obtaining such observations with aircraft-based oceanographic lidar instruments, and will conduct basic research that could lay the foundation for future space-based observations.

2.3.1.1 Systematic Global Observations for Ocean Ecology and Biogeochemistry

The highest priority requirement for ecological research in the ocean is to assemble a long-term record of global ocean chlorophyll and productivity measurements. The existing time series, which establishes the variability in the ecosystem, began with the CZCS (1978-1986). After a 10-year hiatus, it was resumed with the Ocean Color and Temperature Scanner (OCTS, 1996-1997), and then with SeaWiFS (launched in 1997). Global ocean color observations will continue with MODIS on the EOS Terra and Aqua spacecraft, the Medium Resolution Imaging Spectrometer (MERIS) on the European Environmental Satellite (ENVISAT), and the Global Imager (GLI) and Polarization and Directionality of Earth’s

Reflectance (POLDER) instruments on Japan's Advanced Earth Observing System (ADEOS-2) satellite. Other ocean color sensors include the Modular Optoelectric Scanner (MOS, a German-Indian collaboration) and India's Ocean Color Monitor (OCM). In collaboration with national and international partners, NASA plans to combine ocean color measurements from existing and future satellite missions to produce a coherent, long-term time-series of global oceanic primary productivity data spanning several decades. NASA is a sponsor of the International Ocean Color Coordinating Group (IOCCG), an affiliate organization of the international Scientific Committee on Oceanic Research (SCOR), which provides a forum for the exchange of information and technical guidance on ocean color measurements between space agencies with current or planned ocean color satellite missions. NASA also participates in the International Global Observing Strategy (IGOS) partnership involving the Committee on Earth Observation Satellites (CEOS) other international organizations.

The ESE plan for continuing acquisition of moderate spatial and spectral resolution imaging radiometer data is to promote the convergence of operational observation requirements with the scientific requirements of the EOS program. In the long-term, NASA plans to rely on the measurements acquired by the next-generation imaging sensor (see Box 1) on the National Polar-orbiting Operational Environmental Satellite System (NPOESS). The transition from EOS global imaging to the NPOESS program will be assured by a bridging mission (see Box 3) covering the intermediate period 2005-2009.

Box 1
Global Productivity Mission

In the long term, NASA's nominal plan is to rely on the NPOESS program for systematic moderate resolution imaging of the Earth surface and atmosphere. Consultations between NASA and the NPOESS Program Office are underway to develop a Visible and Infrared Imaging Radiometer Suite (VIIRS) that could fulfill the observation needs of both scientific and operational users. A joint bridging mission (NPOESS preparatory project) is planned in 2005 to fly a prototype of this instrument and ensure observation continuity between EOS and the first NPOESS mission in 2008-2009 (See also Box 3).

Spatial resolution on the order of 250 –1000 m is required for monitoring terrestrial and marine productivity, vegetation type, phenology, cloud cover, fire occurrences, and snow and ice cover. Frequent observation (revisit time on the order of 1-2 days) is essential to capture relatively rapid changes (time scales on the order of a week) that occur during a growing season. Spectral channels similar to those provided by MODIS are required in order to retain similar basic retrieval algorithms and deliver products compatible with EOS records.

The satellite data analysis project primarily associated with systematic observations is the SIMBIOS Project. SIMBIOS was initiated in 1997 to address specifically the challenge of merging ocean color data from different sensors. SIMBIOS must rely on *in situ* measurements (optical and biological properties of the ocean and atmospheric observations) for calibration of satellite observations and validation of remote sensing products. As additional ocean color data sets become available, the SIMBIOS project will continue to conduct intercomparisons of sensor characteristics and retrieval algorithms, and improve calibrations. The ESE will maintain optical instruments at several mooring sites for calibration and validation of satellite ocean color instruments, including the Marine Optical Buoy (MOBY) located off the Hawaiian Island of Lanai, and will help support long-term optical moorings sponsored by other agencies or countries. As part of the SIMBIOS program, NASA co-sponsors validation cruises with other countries.

2.3.1.2 Exploratory Satellite Missions for Ocean Ecology and Biogeochemistry

Despite progress in ocean color remote sensing, as demonstrated with SeaWiFS, the derivation of oceanic primary productivity and the study of biogeochemistry from space is still very much information-limited. Currently, satellite sensors measure only a snapshot of the reflective and radiative properties of the ocean at a few wavelengths; and there is no information regarding depth. Promising remote sensing technologies now in development and new data products from global optical imagers (to be launched in 2002-2005) are expected to meet these limitations. These new technologies include (1) hyperspectral remote sensing, (2) the measurement of fluorescence properties of surface waters, (3) oceanographic lidars, and (4) imaging of episodic variability. In addition to these new technologies, there is also a need for improved atmospheric correction techniques in coastal regions as well as the open ocean. This effort will benefit from new remote sensing technologies for measuring atmospheric aerosols (see Chapter 4 on Atmospheric Chemistry, Aerosols, and Solar Radiation), and new developments in modeling the optical properties of absorbing aerosols and mineral dust. There is also interest in a proposed atmospheric carbon dioxide mission for identifying and quantifying oceanic carbon source and sink regions (see TEB, section 2.3.2.2).

Hyperspectral Observations and Data Analysis

Very-high spectral resolution (~10 nm) imaging spectrometers allow the discrimination of various components in seawater, including the identification of key taxonomic or functional groups of phytoplankton. Phytoplankton are classified based on their pigment composition, and the different pigments have characteristic absorption maxima. If the different pigments can be discriminated using space-based spectrometers, then the structure of the phytoplankton community can be estimated. Likewise, coccolithophore blooms can be detected by the anomalously high reflectance of their calcite covering. Nitrogen fixers also may be identified through their specific pigment signatures. Improved spectral and spatial resolutions will lead to new techniques for detecting harmful algal blooms and for mapping and monitoring coral reef ecosystems.

Coral reefs occupy a potentially significant fraction of the tropical ocean, but estimates of their areal extent vary by an order of magnitude. NASA plans to map the Earth's coral reefs in a hierarchical manner, using a combination of space-based sensing, aircraft missions, and *in situ* studies. Large-scale mapping, encompassing the tropics for example, will be done at low resolution (1-4 km) using the satellite sensors for ocean color (SeaWiFS, MODIS). Landsat 7 (see LCLUC, section 2.3.3.1) is collecting relevant high-spatial resolution data (30 m) over selected coral reefs. A major part of the effort will be to develop hyperspectral techniques for identifying reef structures, classifying types, and monitoring reef health. Hyperspectral sensors are available on aircraft, and will be used in conjunction with *in situ* studies.

Both NASA and other groups plan to deploy hyperspectral imagers in the near future. The NMP Earth Observing-1 (EO-1) technology demonstration mission was launched in November, 2000. The Department of Defense (DOD) also has plans for experimental hyperspectral imaging missions. NASA will continue to utilize airborne hyperspectral sensors, such as the Airborne Visible Infrared Imaging Spectrometer (AVIRIS), over coastal waters and coral reefs. Although MODIS and GLI are moderate spectral resolution sensors, they do have a few very narrow spectral bands that will provide insight for future experimental hyperspectral endeavors.

Fluorescence Properties

MODIS (on EOS Terra and Aqua) and the Global Imager (GLI) on ADEOS-2 will have detectors (sensitive in the red part of the spectrum) for measuring phytoplankton fluorescence. This is an important development in at least two respects. First, fluorescence is a property of phytoplankton only. Thus, in coastal, Case-2 waters, where ocean color observations are confounded by other absorbing components, the phytoplankton can be measured in a different way, and therefore the productivity of coastal waters can be estimated with greater accuracy. Second, the ratio of fluorescence to chlorophyll (where the amount of chlorophyll can be estimated), the "fluorescence yield," provides an indication of the physiological condition of the phytoplankton, and, thus, can be used to increase the accuracy of productivity estimates that are otherwise based on chlorophyll alone.

Vertical structure

Lidars offer the possibility of measuring the vertical structure of the upper ocean in terms of hydrographic as well as biological structure. Oceanographic lidars are currently being evaluated as aircraft-based instruments. The results of these studies will be used to guide future ESE technology investments that could advance such observations for consideration on satellite missions in the latter part of this decade.

Event Imaging

Ocean color satellites generally provide global imagery at time scales, typically, of a week, and miss important dynamics. There are processes in biological and physical dynamics of the ocean that occur on time scales of hours to days. Tidal cycles are important for coastal ocean dynamics, and resolving the tidal cycle is a critical requirement that can only be fulfilled by at least hourly observations from a geostationary platform. Understanding of changing coastlines and coral reefs would also benefit by monitoring at high temporal resolution. There are two missions that will support dynamical studies in coastal regions. First, the "Special Events Imager" (SEI) has been proposed as a joint NASA-NOAA operational prototype sensor to provide event imaging capability on GOES geostationary satellites (Kennel et al, 1999). The SEI will offer, for the first time, the study of very short time-scale ocean dynamical processes at specific locales. Second, the International Space Station's (ISS) Window Observational Research Facility (WORF) is being considered for mounting hyperspectral sensors to monitor change and study dynamics in coastal and coral reef ecosystems. ISS can revisit desired sites daily and has other operational characteristics (such as instrument turn-around), that can make it a more efficient means of collecting data than a free-flying satellite.

2.3.1.3 Field Campaigns and Process Studies for Ocean Ecology and Biogeochemistry

Field campaigns for ocean ecology and biogeochemistry are conducted to validate data retrieved from satellite sensors. They may be designed, for example, to provide data over a range of environmental variability in order to establish algorithms for converting the color of the ocean to plant pigment values quantitatively. Field campaigns are a major component of the SIMBIOS project. After a satellite is launched, a complete suite of ocean optical measurements is needed for initial validation of the satellite sensor. Later in the life of the sensor, validation cruises are required to characterize sensor degradation, or to aid in the development of improved algorithms.

Process studies conducted from ships are needed to understand the linkage between physiological and biogeochemical processes, which take place at very short time and space scales, and the optical properties of the water. They are important for putting the satellite observations into an oceanographic context. The strategy aims to progress beyond empirical or statistical relationships between *in-situ* and remote-sensing measurements, and achieve a more mechanistic or theoretical understanding.

Coordination of shipboard and satellite studies is mutually beneficial: satellite data extend shipboard measurements in space and time, and shipboard research allows interpretation of large-scale satellite observations in terms of oceanic processes. With the exception of calibration/validation cruises in support of a particular satellite sensor, NASA does not normally sponsor ship-based research campaigns, but supports the participation by individual U.S. scientists in campaigns sponsored by other agencies or research institutions. NASA's role is primarily to provide satellite or airborne remote sensing data in support of these major campaigns.

In the past, NASA has supported investigators in the Joint Global Ocean Flux Study (JGOFS), the Ecology and Oceanography of Harmful Algal Blooms Program (with NOAA, NSF, EPA, and ONR), and the Coastal Intensive Site Network (with EPA and NOAA). There are three candidate programs on the ocean's carbon cycle, successors to JGOFS that are now in the planning stage, with which NASA will likely cooperate in the future. SOLAS (Surface Ocean - Lower Atmosphere) will focus on fluxes across the air-sea interface. OCTET (Ocean Carbon Transformations, Export and Transfers) has a more biogeochemical orientation, and will center on carbon and nutrient fluxes throughout the ocean's water column. EDOCC (Ecological Determinants of the Ocean's Carbon Cycle) will focus on the effect of ecosystem dynamics on the carbon cycle. NASA plans to participate in planning these programs to understand the ocean's carbon cycling dynamics, to offer guidance in terms of satellite and airborne missions, and to participate in implementation of process studies. Another way in which NASA supports process studies is by coordination with international partners through the IOCCG and the IGOS partnership.

In addition, NASA will support at-sea process studies of the role of phytoplankton as sources of methyl bromide and dimethyl sulfide compounds, and of the influence of such emissions on atmospheric chemistry and climate. Research in this area is expected to provide a basis for combining satellite-derived phytoplankton and physical data to estimate natural sources of these gases.

2.3.1.4 Modeling for Ocean Ecology and Biogeochemistry

Ocean ecology and biogeochemistry are at the heart of pressing environmental and social problems, and the scientific community will increasingly be asked to produce predictive models of demonstrable skill. For example, in the coastal zone, society will need to know potential outcomes and hazards associated with development and resource exploitation. Both predictive and diagnostic models will be used in the development of system models for the coastal zone (land-ocean models) and for the open ocean (ocean-atmosphere models). Over the next decade, NASA will participate in the development of coupled land-ocean-atmosphere models.

Modeling of ocean ecosystems is limited by the availability of observations covering large regions, and the continued availability of extensive marine observations, feasible only with satellites, is crucial for continued model development. We are not yet able to reproduce the variability of the surface ocean in models, and this reflects our lack of understanding of the forces affecting biological variability. In terms of the global carbon cycle, a major unknown is the magnitude and variability of the biological pump which has a significant impact on the distribution of carbon as well as the other elements. In this regard, models of the carbon cycle will, of necessity, have to include interactions with phosphorus, nitrogen, silica, and iron.

NASA will assist in the development of data assimilation schemes and coupled biological-physical models to link surface ocean color measured by satellites to the underlying physical dynamics in order to capture the dynamical behavior of phytoplankton communities over the full depth of the euphotic zone. These models will be extended to include effects on higher trophic levels, including those relevant to fisheries (NRC, 1992).

The overall objective is to be able to combine the time series of observations (aided by calibration and validation field campaigns), process studies, and new types of remote sensing measurements, to obtain a better understanding of the ocean's carbon cycle. These studies must be linked to studies of the physical processes that force, and the chemical processes that are affected by, biological dynamics. Heat fluxes and wind drive changes in biological processes and carbon dioxide fluxes in the surface ocean. Phytoplankton growth and decay affect the ocean's chemistry, and also that of the overlying atmosphere. Models test our understanding of these relationships, and NASA will generate models, validate their output at global scales, and predict future outcomes for the environment.

2.3.2 TERRESTRIAL ECOLOGY AND BIOGEOCHEMISTRY (TEB)

The goal of ESE's terrestrial ecology and biogeochemistry research is to improve understanding of the structure and function of global terrestrial ecosystems, their interactions with the atmosphere and hydrosphere, and their role in the cycling of the major biogeochemical elements and water.

This program element addresses variability in terrestrial ecosystems (Question V3), their role in responding to and affecting global environmental change (Question R2) and in the global carbon cycle (Questions R2 and P5). Land cover and land use change (Questions F2 and C2) are not addressed directly, but are considered among the forcings to and responses of ecosystems.

The research approach combines:

- use of remote sensing to observe terrestrial ecosystems and their responses;
- field campaigns and process studies to elucidate ecosystem function; and
- ecosystem and biogeochemical cycling models to predict responses.

Current research emphasizes analysis of:

- ecosystem responses to change;
- terrestrial productivity;
- carbon cycling; and
- land-atmosphere interactions and feedback to climate and atmospheric chemistry.

Ecosystem Responses to Change

The USGCRP is currently highlighting a need to understand the responses of ecosystems to multiple stresses, including the combined impacts of changes in climate (e.g., changes in the frequency and occurrence of extreme events), air and water pollution, atmospheric carbon dioxide concentration, and nutrient availability (USGCRP, 1999; NRC, 1999). Response to disturbance is an area of growing priority as well. The research strategy to understand the effects of multiple, interacting environmental stresses and disturbances on ecosystems includes field campaigns to acquire comprehensive data sets, fundamental process studies, and manipulative field experiments to quantify the integrated effects of multiple changes (e.g., free-air carbon dioxide enrichment experiments combined with nutrient or moisture manipulations). ESE field campaigns are conducted to provide the needed comprehensive data sets, as well as certain process studies. Other agencies will lead in conducting other process studies and the needed manipulative field experiments. NASA will limit its involvement in such experiments to support of remote sensing-oriented activities using its unique observing capabilities. In general, ESE will support analyses of space-based observations of ecosystem responses, especially time series of data, to document large-scale response patterns and derive understanding of the processes of change. In addition, ESE will support model development activities that incorporate responses to multiple stresses.

Terrestrial Productivity

Research to observe and understand patterns of change in global primary productivity will continue to be an ESE priority because of its direct relevance for understanding food production, ecosystem health, and the global carbon cycle. Patterns of terrestrial NPP vary greatly from region to region and from year to year, as recent regional food surpluses and famines illustrate dramatically. Daily, seasonal, and annual primary productivity can be monitored from space using spectroradiometers sensitive to visible and near-infrared wavelengths. Terrestrial productivity is characterized in terms of vegetation indices or relationships with remotely sensed biophysical properties, such as the leaf area index (LAI) or the fraction of absorbed photosynthetically active radiation (fAPAR). Analysis of vegetation development over the course of a growing season provides useful estimates of annual NPP and yields, as well as predictions of food shortages. ESE plans to continue producing global data sets of vegetation indices and biophysical properties as a means of estimating primary productivity, with increased emphasis on quantitative analysis of data from a new generation of satellite sensors.

Carbon Cycling

The new USGCRP initiative on Carbon Cycle Science seeks information on the fate of carbon in the environment, including the partitioning and exchanges of carbon among the various active reservoirs, and carbon transfer between the terrestrial biosphere and the atmosphere caused by human activities (USGCRP, 1999; Sarmiento, et al., 1999). ESE will contribute to this initiative by leading in the provision of satellite-based estimates of primary productivity, documentation of the global distribution of carbon sources and sinks, and exploration of new remote-sensing methods for inferring above-ground biomass or measuring other carbon cycle components. New satellite observations of fire occurrence, spatial extent, and temperature will provide an observational foundation for analyzing biomass loss due to fire and related trace gas emissions to the atmosphere. ESE will partner with other agencies in the conduct of process studies and the development of improved global and regional carbon cycle models.

Land-Atmosphere Interactions

Research on land-atmosphere interactions supports ESE studies of land hydrological processes and atmospheric chemistry in order to advance integrated Earth system science. With regard to climate and the global water cycle, the objective is to understand how changes in ecosystem properties and processes affect factors such as surface albedo and net radiation, the partitioning between latent and sensible heat fluxes, aerodynamic roughness, boundary layer properties, and aerosol emissions, and, thus, control exchanges of energy, water, and particulate matter. Of particular interest is how knowledge of these interactions can be used to improve weather forecasts and climate predictions. Cooperation with the Global Water and Energy Cycle program element (see Chapter 2) is important for these interactions. ESE's terrestrial ecology and biogeochemistry program element will investigate these interactions and feedback mechanisms through satellite data analysis, major field campaigns, and improvements to interactive Earth system component models.

With regard to interactions with atmospheric chemistry, research in terrestrial ecology and biogeochemistry will emphasize quantitative understanding of emissions of radiatively and chemically important trace gases and particulates from terrestrial ecosystems. The redistribution and deposition of nutrients by the atmosphere is also of interest. Coordination with the Atmospheric Chemistry program element (see Chapter 4) is important in this regard. Actual observation of trace gas emissions and nutrient deposition, and relevant process studies fall within the responsibilities of other USGCRP agencies (NSF, EPA, DOE, USDA). However, NASA has contributed by developing *in situ* measurement technologies and supporting trace gas observations and process studies in the field -- primarily of methane and nitrous oxide. Future efforts will be focused on improving estimates of regional and global trace gas emissions and carbon and nitrogen budgets using enhanced data analysis methods and models. Satellite observations of fires will provide an observational foundation for assessing releases of trace gases and particulates to the atmosphere. Trace gas observations and process studies will be conducted primarily in the context of major field campaigns.

Consequences

A difficult scientific challenge is to quantify the implications of terrestrial ecosystem changes for sustained provision of food, fiber, and ecological services in the face of a growing human population, climatic variations, and other environmental stresses. Changes in the productivity, carbon storage, biodiversity, and health of both managed and unmanaged ecosystems can have significant implications for local, regional, and global economies and for the quality of life. Research in this domain will be pursued in cooperation with the ESE Applications programs (e.g., joint research on productivity and the impacts of fires), as well as other government agencies, to deliver information needed for environmental assessments and decision-making.

2.3.2.1 Systematic Global Observations for Terrestrial Ecology and Biogeochemistry

Observations of terrestrial ecosystems at fine spatial and fine temporal resolutions are required to address the science questions for terrestrial ecology and biogeochemistry. High spatial resolution data are required to characterize ecosystem processes and responses to environmental changes at a spatial scale close to that at which the causal factors operate and the initial responses occur. High temporal resolution data are required to capture short-term physiological responses, phenological events, and interactions with the changing environment, and, in the case of optical sensors, to increase the frequency of cloud-free observations. Since a single satellite instrument combining high spatial and high temporal resolutions remains beyond current technical capabilities, the observational strategy is based on simultaneous deployment of instruments with inversely related spatial and temporal resolutions. Thus, the highest priorities for satellite observations are for continued systematic global measurements of (1) vegetation indices and biophysical properties at moderate spatial resolution (0.5–1 km) with near-daily sampling frequency, and (2) land surface multispectral reflectance at high spatial resolution (30 m) as frequently as possible (now about 16 days).

Moderate spatial resolution, high temporal frequency data will be used to generate and improve global estimates of terrestrial productivity and carbon sequestration, to characterize phenology, and to analyze changes over time. Global data sets are needed also for use in Earth system models and to validate model predictions. These observations will extend the time series started in 1981 with Advanced Very High Resolution Radiometer (AVHRR) measurements on NOAA’s polar orbiter series and continued with MODIS measurements on the EOS Terra and Aqua missions. Major advances in quantitative retrieval of vegetation and surface biophysical properties are expected from the improved performance, characterization, and absolute calibration of the MODIS instrument. NASA's plan for continuation of these observations is to cooperate with NOAA and the DOD to effect the convergence of the research and operational observation programs in this area and, eventually, rely on NPOESS and other future global operational observing systems. A single bridging mission, the NPOESS Preparatory Project, carrying the first VIIRS instrument is needed to fill the 2005-2009 gap between MODIS and the first NPOESS VIIRS flight.

High spatial resolution data will be used in support of local- to regional-scale process studies and field campaigns and for quantitative analysis of terrestrial ecosystem changes and carbon cycle components. The high spatial resolution observations will extend the time series started in 1972 with Earth Resources Technology Satellite 1 (Landsat 1) and continued today with Landsat 7. Other high spatial resolution optical and microwave observing systems provide complementary information and will be used to enhance temporal sampling, mitigate cloud cover problems, or incorporate new information. A series of land imaging missions following Landsat 7 is required. Each mission would carry an instrument capable of producing multispectral (visible through short-wave infrared) imagery at fine (~10-30 m) spatial resolution and of obtaining global coverage seasonally. The instrument concept for the next such mission could be based on the Advanced Land Imager design being tested on the NMP EO-1 technology demonstration mission. In order to meet continuity requirements, this mission would need to be launched in 2005.

Data analysis priorities for the next 3-5 years will focus on exploiting MODIS and Landsat 7 data, and on assuring that these new data sets can be tied to historical records from AVHRR and the Landsat 1-5 sensors. In the 5-10 year time frame, the highest priority for new, systematic satellite observations is to ensure the continuity of these two global data records. Close coordination with potential operational or commercial data providers will be essential to ensuring mutually beneficial partnerships. Use of data from foreign missions (e.g., MERIS, GLI, various SAR instruments) will be necessary to fill gaps and enhance data products. Details of the planned systematic observation missions are provided in Boxes 1 and 2 (see sections 2.3.1.1 and 2.3.3.1, respectively).

2.3.2.2 Exploratory Satellite Missions for Terrestrial Ecology and Biogeochemistry

The need to quantify the carbon cycle, assess patterns of biomass change, and understand ecosystem responses to disturbance drives the requirements for future exploratory satellite missions. Missions focused on these specific objectives have been proposed (Kennel et al., 1999), as well as innovative exploitation of new satellite observations provided by the EOS program in order to explore a broader range of potential ecological and biogeochemical applications.

Vegetation Canopy Lidar Mission

Measurement of biomass from space would enable greatly improved estimates of terrestrial carbon storage as well as agricultural and forest yields for a variety of practical applications. The ESSP VCL mission proposed to fly an array of five laser altimeters to measure canopy top heights, the vertical distribution of leaves and branches, and ground surface topography over portions of the Earth's surface. The height and vertical distribution of vegetation canopies will be used to generate estimates of above-ground biomass and carbon storage. In the next 2-5 years, ESE-sponsored research on this topic will focus on developing methods for estimating canopy structure and above-ground biomass in support of quantitative analysis of the global carbon cycle.

Vegetation Recovery Mission.

Quantifying the rates, patterns, and degree to which landscapes respond to both anthropogenic and natural disturbance will address a major uncertainty in the terrestrial carbon budget, that is, carbon uptake by secondary, regrowing forests. For this purpose, it will be critical to track, in terms of above-ground biomass, both the occurrence of and recovery from such major disturbances as clear cutting and fires. A proposed post-2002 exploratory research mission to quantify biomass recovery addresses this need (Kennel et al., 1999). The nominal Vegetation Recovery mission measurement strategy requires periodic observations of specific sites subject to major disturbances. A steerable lidar altimeter system, based on technological evolution of the VCL concept looks most promising for this mission, but SAR, multi-angle, and hyperspectral approaches also merit consideration. A complementary visible-infrared imager might be necessary to document the recovery of non-forest ecosystems. In addition, an ability to obtain hyperspatial data (~1m) is desired to enable characterization of fine-scale, sub-pixel spatial patterns and vegetation structure. It is envisioned that this exploratory mission could be implemented on a small spacecraft and aim for a 3-5 year life time to start during the 2007-2009 period, and that the hyperspatial data might be acquired through a data purchase. Despite the current high priority accorded carbon cycle science, this mission is proposed for selection and development only after the results of the VCL, Multi-angle Imaging Spectroradiometer (MISR), EO-1, SRTM, and other SAR (Japanese, Canadian, European) missions have been fully evaluated and the merits of their respective technologies assessed for this scientific application.

Atmospheric Carbon Dioxide Research Mission

Every region of the Earth's surface with a major carbon dioxide source or sink leaves a signature of excess or depleted carbon dioxide in the overlying troposphere. Available *in situ* measurements of near-surface atmospheric carbon dioxide concentrations have been used recently to constrain inverse models (see the section on inverse modeling in Chapter 7) of atmospheric transport and predict hemispherical scale distributions of carbon sources and sinks. However, deficiencies in the geographic coverage and spatial distribution of these observations severely limit the utility of the inverse modeling approach. An ability to make direct space-based measurements of atmospheric carbon dioxide concentrations, with sufficient accuracy and precision, would provide the needed global coverage and overcome problems with surface measurements within continents. Such observations would make it possible to identify, and at least roughly quantify, regional and sub-regional sources and sinks of carbon dioxide and to further constrain the location and/or identity of the missing global carbon sink(s). Advances in solid-state laser technologies suggest that it may be possible to make precise active remote sensing measurements of the total column and vertical profile abundance of carbon dioxide. Simulations also show that a high resolution spectrometer employing solar flux reflected from the ground could possibly provide precise measurements of total column carbon dioxide. Measurements of the carbon and oxygen isotopic composition of atmospheric carbon dioxide also might be possible. NASA is in the early stages of conducting an assessment of the potential for such space-based carbon dioxide measurements and is beginning to define the requirements for what could lead to a future mission focused on carbon cycle dynamics. This mission concept was first suggested after the post-2002 mission planning activity was completed and has yet to undergo a full science community review and priority assessment process.

Hyperspectral Observations and Data Analysis

Recent research with airborne hyperspectral sensors has demonstrated that very high spectral resolution (~10 nm) observations can be used to improve discrimination of vegetation types, phenological stage, canopy chemical composition, and physiological status well beyond what is now possible with multispectral instruments. Many of these applications require continuous spectra over some significant portion of the visible to short-wave infrared spectrum (0.4-2.5 µm). The NMP EO-1 technology demonstration mission will provide the first hyperspectral images from space. Terrestrial ecology and biogeochemistry research using EO-1 and other hyperspectral data (e.g. DOD Warfighter-1, NASA AVIRIS) will focus on advancing the applications for canopy chemistry and physiological status. Relationships between hyperspectral reflectance properties and canopy chlorophyll content, non-photosynthetic constituents, stress, and moisture status have been well-demonstrated. Correlation between canopy nitrogen and lignin content and hyperspectral reflectance continues to be seen, but not consistently, and the biophysical basis for the relationship remains elusive. Hyperspectral data have also shown promise for detecting and monitoring the spread of certain invasive plant species. NASA's plans for satellite hyperspectral data beyond the time frame of EO-1 depend very much on potential commercial and international initiatives and opportunities.

Cold Climate Land-Surface Process Research Mission

The Cold Climate Land-Surface Process research mission (see Land Surface Processes and Hydrology section, 4.3.3.1) addresses an ecosystem property of critical importance for refining estimates of the global carbon balance at high latitudes. Observation of freeze-thaw transitions in vegetation and soils would enable accurate estimates of the length of the growing season, which is the primary determinant of annual carbon uptake in high latitude terrestrial ecosystems. In particular, recent results from the U.S.-Canada Boreal Ecosystem-Atmosphere Study (BOREAS) have shown that the timing of springtime thaw can largely determine the annual uptake of carbon by boreal forests. The measurement concept for this mission is based on SAR imaging at moderate spatial resolution (~1 km) to detect freezing conditions at the surface. The primary payload would be a two-polarization, high accuracy SAR system at L-band or lower frequency. Moderate spatial resolution would allow complete coverage at high latitudes with a short repeat cycle (~3 days). NASA intends to investigate potential commercial and international initiatives in this domain.

Exploitation of New Satellite Observations

In the next few years, an unprecedented diversity of satellite data will become available for exploring new remote sensing applications in terrestrial ecology and biogeochemistry. The spectral resolution and dynamic range of MODIS will enable improved assessment of the occurrence, size, and temperature of fires. MISR will enable greatly improved estimates of surface albedo and analysis of vegetation canopy vertical structure. The Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) will provide the first multispectral thermal imagery at high spatial resolution. Global topographic data from the Shuttle Radar Topography Mission (SRTM) (see section 6.3.4 on Global Geology Studies) will be used as input to ecological models and to aid in satellite data corrections. Synthetic aperture radar (SAR) systems (see section 6.3.4) will allow further evaluation of disturbance, vegetation regrowth, and above-ground biomass; L-band or lower frequency sensors will be most useful. There is strong interest in continuing the scientific collaboration with Japan that was initiated to map forest cover and inundation under the JERS-1 Global Rain and Boreal Forest Mapping Project (GRBFM); Japan's Advanced Land Observing System's (ALOS) Phased Array type L-band Synthetic Aperture Radar (PALSAR) to be launched in 2002 offers such an opportunity. There also is an emerging interest in exploring the application of geostationary satellite observations to studies of the diurnal cycle of fire activity. Research investments in each of these areas will not be large, but, rather, will be focused on evaluating the potential utility of the remote sensing techniques for specific ecological applications and identifying those most promising for future use.

Supporting Hydrological and Climatic Observations

Many scientific issues in terrestrial ecology and biogeochemistry can only be addressed when high-quality supporting hydrological and climatic satellite data sets are available. For example, systematic observations of surface temperature, humidity, and incident solar radiation are needed to drive ecological models, and information on clouds and atmospheric aerosols is needed to correct surface imagery. Such dependencies on observations obtained under other themes within the ESE must not be overlooked, and several post-2002 exploratory mission concepts offer exciting possibilities as well.

Soil moisture and rainfall are important climate-related controls on ecosystem productivity and carbon dynamics. The Soil Moisture research mission (see section 4.3.3) is of interest for characterizing near-surface soil moisture in sparsely vegetated ecosystems. If the measurement approach for this mission could be made more sensitive to soil moisture in regions of moderate to dense vegetation, and the spatial resolution increased, this mission would have even greater value. The Global Precipitation mission (see section 4.3.1) also is of interest if it can provide improved estimates of rainfall over land at ecologically-relevant spatial resolutions. Aerosol measurements (see section 3.3.1) are needed for improved atmospheric corrections and information on fire emissions. The Surface Water Level Monitoring mission (see section 4.3.3) is of interest for information on water flows from terrestrial to aquatic and marine ecosystems because of the implications of such water flows for biogeochemical cycling.

2.3.2.3 Field Campaigns and Process Studies for Terrestrial Ecology and Biogeochemistry

Major Field Campaigns

Field campaigns designed to address a specific global change science question and support comprehensive study of the relevant processes are a major element of ESE terrestrial ecology and biogeochemistry research. These campaigns typically involve coordinated *in situ*, airborne, and spaceborne observations of a particular site or region of the world, or along a gradient of environmental change.

The principal field campaign for 1999-2003 focuses on understanding the effects of tropical forest conversion to agricultural uses in Amazonia. This work is part of the Brazil-led Large-Scale Biosphere-Atmosphere Experiment in Amazonia (LBA). The topics addressed by NASA's ecological contribution to LBA (LBA-Ecology) include land cover and land use change (see LCLUC program element, section 2.3.3.2), carbon storage and exchanges, nutrient dynamics, and trace gas fluxes. Research on terrestrial carbon and nutrient dynamics involves quantification of the carbon and nutrient stocks in vegetation and soils of intact forests and savannas, pastures, cultivated lands, and second-growth and selectively-logged forests, as well as quantification of the rates of carbon and nutrient exchange among the atmosphere, vegetation, soils, and surface waters. This work will contribute to carbon cycle science by helping to reduce uncertainty in current estimates of the tropical deforestation carbon source, and also will help to quantify rates of carbon sequestration in re-growing, secondary forests. LBA-Ecology research on trace gas fluxes is focusing on quantification of the fluxes between the biosphere and the atmosphere and their controlling factors, with first priority accorded to nitrogen oxides and methane.

Local-scale measurements and process studies under LBA-Ecology will be conducted for a period of 3-5 years along gradients of land use intensity and seasonality of rainfall. The results will be used, in combination with regional-scale remotely sensed data and geographic information system (GIS) databases, to develop and validate models. A distributed data and information system (LBA-Ecology DIS) will enable data exchange among investigators and facilitate transfer to the public archives for LBA-Ecology at the Oak Ridge National Laboratory (ORNL) Distributed Active Archive Center (DAAC) and in Brazil. A partnership between LBA-Ecology DIS and a cluster of ESIPs has been formed to share data analysis tools and enhance tropical forest data availability and distribution. EOS instrument performance and data product evaluation will be conducted as part of LBA. LBA-Ecology research is closely coordinated with NASA's LBA-Hydrometeorology research (see section 4.3.3) and will benefit from the recent Tropical Rainfall Measuring Mission (TRMM-LBA) validation campaign in Brazil (see section 4.3.1).

NASA is making a substantial contribution to the Southern African Regional Science Initiative 2000 (SAFARI 2000) with cross-disciplinary sponsorship of several ESE program elements and led by the MODIS Science Team. The campaign aims to examine land-atmosphere interactions and characterize biogenic, pyrogenic and anthropogenic aerosol and trace gas sources and sinks in southern Africa. Results will be evaluated by comparing atmospheric transport and land-surface process model outputs with ground-based, airborne, and satellite-based observations. The campaign will take place across an environmental gradient from semi-arid grasslands to humid tropical woodland and covers a range of land use types. The field program includes satellite validation science focused on validating data products from the new instruments on the EOS Terra and Aqua platforms. The campaign will be conducted in 1999-2002.

Smaller-scale field campaigns focused on the evaluation of satellite sensor performance and validation of data products have been planned and can be expected to continue in association with the launch of new satellite missions. Validation of EOS data products will make use of a global network of test sites which includes long-term ecological research (LTER), Global Terrestrial Observing System (GTOS), and globally distributed flux tower (AmeriFlux and FluxNet) sites (NASA, 1999). Field campaigns to occur beyond 2003 will be planned in the near future.

Airborne Observations

Remote sensing and *in situ* observations from airborne platforms are key to the scaling strategy of major field campaigns; they provide the intermediate scale of observations bridging from the local-scale of field plots to the synoptic scale of satellite-sensed pixels. Airborne simulators or prototypes have been developed for many of the new satellite sensors and will be extensively used for validation in the upcoming years. Airborne sensors also provide unique data sets employing technologies not yet ready for or feasible from space that directly address priority science questions. Examples include the AVIRIS and the Advanced Solid-state Array Spectroradiometer (ASAS) that have been sources of hyperspectral and multi-angle data, respectively, for the past decade and, potentially, the airborne Lidar-Induced Fluorescence Transient sensor now being developed under the IIP to measure laser-induced fluorescence for estimation of photosynthetic efficiency in terrestrial vegetation.

In Situ Measurements

In situ observations are made and supporting data sets are assembled primarily (1) for systematic evaluation of satellite sensor performance and data product validation, (2) to provide customized input and test data for models, and (3) in support of specific field campaigns. NASA is currently supporting a number of carbon dioxide flux measurement towers (as a participant in the Department of Energy's AmeriFlux network and as a lead sponsor of the international FluxNet) to support validation of EOS NPP data products and NEP models and to study factors governing carbon fluxes from terrestrial ecosystems. This NASA investment in *in situ* observations is not intended to provide long-term monitoring.

Basic Remote Sensing Research

Basic research on the interaction of electromagnetic radiation with terrestrial ecosystems provides a theoretical basis for the utilization of remotely sensed data. Such research advances our ability to extract quantitative information from remotely sensed data. It also provides a theoretical foundation for developing new scientific applications of remotely sensed data and for identifying the signals of life that are of interest in Astrobiology for detecting life elsewhere. Future research will emphasize work that aids in the interpretation of data from upcoming satellite missions. Examples of priority research areas are: biophysics of laser profiling of vegetation canopies, cross-satellite calibration and atmospheric correction, intercomparison or fusion of data from complementary sensors (e.g., MODIS-AVHRR, Landsat-SAR), and inversion of simplified canopy models for biomass estimation.

Process Studies

Process studies to elucidate the physical, chemical, and biological controls on ecosystem responses to change are conducted principally in the framework of field campaigns. The terrestrial ecology and biogeochemistry program element conducts process studies to: (1) obtain information necessary for interpreting remotely sensed observations, (2) improve the formulation of key process mechanisms in ecological models, or (3) identify useful remote sensing surrogates for critical controlling factors. Future process studies will focus on obtaining the information needed to improve models of carbon dynamics. Other process studies will be conducted to advance our ability to incorporate into models the effects of multiple interacting stresses or to characterize and model trace gas dynamics. There is renewed interest in cross-disciplinary research focused on reducing uncertainties in our understanding of the global methane budget. Equally compelling, is a proposed cross-disciplinary effort on the role of fire in accounting for global trace gas and aerosol emissions to the atmosphere and in ecosystem nutrient cycling.

2.3.2.4 Modeling and Integration for Terrestrial Ecology and Biogeochemistry

The ability to understand and predict terrestrial ecosystem responses to environmental change, especially those responses that may take decades or even centuries to unfold, depends on our ability to model ecosystem functional and structural dynamics over a range of time scales. The objective is to develop realistic models that correctly portray key mechanisms and controlling factors and account for all important influences (e.g., multiple stresses, disturbance) on ecosystem function. The challenge is to make the models as simple and robust as possible without losing realism and useful predictive capacity. The modeling strategy requires a suite of ecological and biogeochemical models of varying complexity that operate over different spatial and temporal scales.

Modeling approaches to span spatial scales often nest fine-scale, process-level models hierarchically within one or more coarser-scale component models as a means of passing process understanding to regional scales and, ultimately, into global models. Remotely sensed data on land cover spatial pattern can be used to stratify a landscape so that process parameterizations or sub-models can be associated with cover types and then applied across the region being modeled. Presently, few of these nested modeling schemes are fully interactive, but that is a goal for the future. Lateral exchanges and storage of water, carbon, and nutrients are poorly represented in most current models, and this aspect of spatial modeling will be a focus for future improvement.

Research to couple models that capture processes operating at differing time scales (i.e., coupling physiological land surface to biogeochemical to successional to biogeographical models) is needed. Already the latest generation of terrestrial biosphere models incorporate a blend of such time varying ecosystem and land surface processes in a consistent framework. Further coupling and integration will be requisite steps toward eventual reciprocal coupling with other Earth system component models (e.g., GCM-type models). This will be absolutely essential for correctly portraying feedback loops – especially those that operate over long time scales (i.e., decades to centuries) and might not be captured in the short time scale models. NASA research will focus on developing and linking the models that take greatest advantage of remotely sensed data sets.

Predictions of future carbon cycle dynamics will require coupled biosphere-atmosphere-ocean models, and research toward this objective will be a priority. Progress has been made in the development of Dynamic Global Vegetation Models (DGVM) that are meant to interactively couple physiological models with climate models, and such research will be continued (IGBP, 1992; NRC, 1999). Strong collaborations across several ESE program elements as well as among many of the USGCRP agencies will be needed to further advance coupled Earth system modeling. NASA intends to be an active partner in this effort, focusing on model development and evaluation research that makes effective use of remote sensing and NASA field campaign data. Research toward other types of Earth system models will be approached in a similar, collaborative fashion.

Current ecological and biogeochemical models are most limited by the availability of high-quality data (especially long time series of data) for initialization or testing and by our understanding of critical controlling processes and interactions among them. Developing, improving, and managing needed input satellite data sets will, therefore, continue to be a priority. So will be the exploitation of new satellite observations (e.g., canopy height, vegetation structure, soil moisture). Process studies within field campaigns and model intercomparisons will be supported to advance our ability to identify and realistically model critical processes. For example, it will be important to better understand processes of carbon allocation, phenology, carbon turnover, disturbance, and succession, and to identify which are most critical to pursue. An ability to correctly portray disturbance has already been shown to be extremely critical.

Other modeling activities will focus on modifying or updating existing models to accept data from the new generation of satellite sensors, especially MODIS, Landsat 7, and VCL. The comprehensive data sets acquired in the BOREAS, LBA, and SAFARI 2000 field campaigns will be exploited for model testing and refinement. These and other data sets assembled and made available through the EOSDIS DAACs and ESIPs are critically needed for advancing global models. Opportunities will be sought within NASA's Astrobiology partnership to exercise Earth system biogeochemical cycling models to explore the co-evolution of life and the changing environment. Modeling is the key tool for synthesis and integration of scientific understanding, but not the only approach available. Analysis of empirical relationships within the framework of a GIS, direct analysis of remotely sensed time-series, and data assimilation also will be conducted.

2.3.3 LAND COVER AND LAND USE CHANGE (LCLUC)

The goal of the NASA land cover and land use change (LCLUC) program element is to develop the capability to perform repeated global inventories of land cover and land use from space and to develop the scientific understanding and models necessary to evaluate the consequences of observed and predicted changes.

This program element addresses land cover and land use changes and their causes and consequences (Questions V3, F2, C2, and C3). An important priority is to assess the impact of changes in land cover and land use on the global carbon cycle (Question C2). This program element recognizes that land cover and land use change can be responses to global environmental change and that they also act as forcings of global environmental change. Of primary interest are: the influence of human actions on land cover dynamics; associated impacts on the global carbon cycle, other biogeochemical cycles, and the global water cycle; and their implications for land management. There is also a desire to pursue fundamental investigations of sustainable land use and biodiversity.

Near-term research objectives for LCLUC research are to:

- document the spatial distribution and rates of change of land cover and land use;
- characterize changes in land cover and land use over the past several decades;
- examine biophysical and human forcings of change in land cover and use; and
- assess and predict the consequences of changes in land cover and land use.

The research approach requires:

- large-scale satellite data analysis and production of validated land cover data sets;
- regional case studies of specific biophysical processes and their social contexts;
- development of techniques for analyzing changes in land cover and use; and
- modeling of systems undergoing land use change.

The primary strategy is to balance the large-scale satellite data analysis with regional case studies that are designed to gain insight into specific biophysical processes and their social contexts. Priority will be given to areas of the world undergoing the most change and where stresses from human activities are likely to increase most rapidly. Key to this strategy are techniques in basic remote sensing and information science for advancing the analysis of changes in land cover and land use. Research to incorporate actual, observed land cover and land use into models is a near-term priority. Ultimately, the ability to model systems undergoing land use change will provide the relevant tool for both scientists and decision-makers to evaluate the consequences of different management practices and policies that affect land cover conversion. In the near-term, emphasis will be on understanding the role of land use change in carbon cycling in forested regions.

Spatial Distribution and Rates of Change

Emphasis is placed on the exploitation of satellite remote sensing data as the best source of information on the spatial distribution of land cover and rates of landscape change on regional, continental, and global scales. Time series of satellite data will be analyzed to (1) provide a consistent record of global land cover change, (2) characterize the end-states of land cover modification in regions of high population density, and (3) study the impacts of spatial patterns and past history of land use on ecosystem processes, biodiversity, and the sustainability of ecological services, such as recycling of nutrients.

Characterize Recent Changes

Improved recognition algorithms will be developed to address the current inadequacies of land cover classification and change detection techniques. Research will be conducted to use high resolution imaging radar data for characterizing basic land cover properties in areas of persistent cloud cover and to derive estimates of above-ground biomass and the extent of wetlands, the latter being directly related to methane and other trace gas emissions. Satellite data will be analyzed to understand long-term changes in the frequency of fire in forests and savannas. Data on land cover distribution and rate of change will be used in the analysis of the effect of spatial patterns and past history of land use conversion on ecosystem processes and structure. In this respect, the acquisition of global land cover data will support environmental assessments.

Biophysical and Human Forcings

The biophysical and human forcing factors that drive changes in land cover and land use are manifested through different phenomena such as fire, drought, flooding, insect infestations, disease, logging, and land clearing. Variability in weather, climate, and internal ecosystem dynamics drive land cover changes on decadal and multi-decadal time scales. Climatic and hydrologic variations and extremes can trigger persistent land cover changes that will, in turn, influence land-atmosphere exchanges for long periods of time. Successive years of drought or above average rainfall, for example, can change ecosystem composition, as well as land use practices or the frequency of fires. Population changes and economic activity are critical factors that determine the distribution and intensity of land cover modification and changes in land use. Pressures for economic development around the world and the demand for increased food production need to be expressed in quantitative terms and ultimately incorporated into models of land cover dynamics. Because ecosystems often respond slowly, understanding current land cover patterns requires taking into account land use history. ESE LCLUC research is linked to the wider effort to incorporate human dimensions into the study of environmental changes, and for the main part, NASA relies on the contributions of its national and international partners for the development of historical and socioeconomic data sets.

Consequences

Land cover conversion, land use intensification, and land degradation are consequences of particular importance for ESE research. Measuring the rates of rapid conversion of forest cover to other types, as is occurring in the humid tropics, and monitoring the fate of deforested land are of particular interest because of the linkages to the carbon cycle, trace gas emissions and tropospheric chemistry, hydrometeorology, biodiversity, and sustainable development. These data also will help in identifying land cover types that require further *in situ* studies in order to parameterize processes in landscape and ecosystem models. Other important research topics are the consequences of intensified management in agriculture, agroforestry, and grazing systems, the assessment of degradation processes in forests, and changes in land use across a region related to human population growth or migration (e.g., the loss of fertile farmland to urbanization).

2.3.3.1 Systematic Global Observations for Land Cover and Land Use Change

Systematic high-resolution satellite observations of the multispectral and multitemporal signatures of global land cover types are essential for study of changes in land cover and land use and their consequences on the storage of carbon, terrestrial productivity, biodiversity, runoff and soil erosion, and for a wide range of applications in agriculture, forestry, and range management. Thus, the foremost observational requirement for LCLUC research is to extend the more than 25-year record of Landsat-type observations, which constitutes the indispensable foundation for global land cover inventories. The Landsat 7 and EOS Terra missions will ensure the continuity and consistency of this essential environmental record for the next 5-7 years. The NMP EO-1 technology demonstration mission, intended to fly in formation with Landsat 7 and the EOS Terra spacecraft, will provide the first flight test of new imaging spectroradiometer designs that should enable future continued high-resolution mapping at much reduced cost. A series of Land Cover Inventory missions are planned for systematic observation of changes in global land cover and land use beyond 2005. Each would carry an instrument capable of producing multispectral imagery at high spatial resolution and obtaining global coverage seasonally (see Box 2 and TEB, section 2.3.2.1).

The principal approach for comprehensive analysis of seasonal, interannual, and decadal variability in the processes of land cover change will be systematic seasonal mapping of the entire global land surface using Landsat 7 and its successor high resolution imagers, ASTER, and/or radar data. Additional data from foreign and commercial satellites will be used when available. Global topographic data from SRTM (see Box 10 in Chapter 6: Solid Earth Science) will be used to refine land cover classifications.

Box 2
Land Cover Inventory Mission

The Land Cover Inventory mission series is intended to maintain the continuity of high-resolution land cover measurements. The required information is multispectral image data in the visible, near, and short-wave infrared ranges of the spectrum, with spatial resolution on the order of 10-30 m. Mid-morning overflight (equator crossing time) is desired. Orbital repeat time on the order of 2 weeks would provide acceptable sampling frequency, although more frequent observations would be desirable.

The New Millennium Program EO-1 mission will demonstrate a new lighter and more compact Landsat-class sensor design that may be applicable to the Land Cover Inventory mission. The sensor will provide similar or better spatial resolution and radiometric accuracy than the Landsat 7 Enhanced Thematic Mapper instrument, and appropriate spectral coverage for atmospheric corrections. The first Land Cover Inventory mission is tentatively planned for launch in the 2005 time frame, with a nominal mission life of 5 years. NASA intends to examine carefully private sector initiatives or potential data purchases as a means to acquire the desired high quality scientific information.

Past land cover and land use studies have been based predominately on AVHRR and Landsat data. A multi-scale approach to land cover characterization and monitoring is intrinsic to the strategy of the LCLUC program element. Many important and useful scientific results have been obtained (e.g. Landsat Pathfinder Humid Tropical Forest Project, Global 1-km Land Cover, and Fire Products) despite the lack of calibration and pointing uncertainties inherent to the AVHRR sensors. NASA has supported the acquisition of a global 1-km AVHRR data set that has proven to be an invaluable data resource for parameterization of land cover in climate and other Earth system component models and for global land cover classification. These early moderate-resolution products provide a context for time-series analysis of data from EOS instruments and their successors. The Global Land 1-km AVHRR Data Set was produced in cooperation with USGS, NOAA, the European Space Agency (ESA), and satellite ground receiving stations worldwide and in scientific dialogue with the International Geosphere-Biosphere Programme (IGBP). This partnership can be viewed as a model for the development of a cooperative strategy for systematic measurements, which must, to be successful, link research, long-term monitoring, and operational programs, including *in situ* observational networks, to provide effective monitoring of our planet on a global scale.

The Global Observation of Forest Cover (GOFC) Project now being implemented under the International Global Observing Strategy (IGOS) partnership follows in this tradition. The goal of GOFC is to develop operational forest monitoring systems to serve the needs of the global change science community, forest managers, and policy makers. This will involve combining satellite and *in situ* data and transitioning research methods and techniques into the operational domain. The NASA LCLUC program element is planning to make a significant contribution to GOFC within the overall international partnership.

EOS/MODIS and EOS/MISR instruments, successor moderate-resolution instruments planned for the Global Productivity Mission (See Box 1), and future operational NPOESS satellites will provide high quality moderate resolution land cover data for the long-term future. SeaWiFS, ESA's Along-Track Scanning Radiometer (ATSR) and the French Vegetation sensor offer complementary sources of 1 km land cover data, as will MERIS and AATSR on ESA's ENVISAT and GLI on Japan's ADEOS II in the near future.

2.3.3.2 Exploratory Satellite Observations for Land Cover and Land Use Change

Several of the exploratory satellite missions detailed in the section on Terrestrial Ecology and Biogeochemistry (2.3.2.2) also address observational needs for Land Cover and Land Use Change research. In addition to the EOS instruments mentioned above, the Vegetation Recovery Mission and hyperspectral observations have important land cover and land use change objectives. VCL is also of interest for measurements of ecosystem structure that can be used to improve land cover classifications. Additionally, the LCLUC program element has a need for hyperspatial data.

Hyperspatial Observations and Data Analysis

Remote sensing imagery with very high spatial resolution (~1 m) from aircraft, and more recently from unclassified national security systems, has proven to be extremely useful for analysis of the sub-pixel composition of imagery from coarser resolution sensors, determination of fine-scale spatial patterns, and inferring land use and management practices from both spatial and temporal patterns. Such hyperspatial imagery is now becoming available from commercial satellite operators (e.g., IKONOS), and purchase of such data for selected case study sites, or to sample sub-pixel variability in other types of studies, is a further option to meet this requirement for LCLUC research.

Vegetation Recovery Mission

The Vegetation Recovery Mission (see TEB, section 2.3.2.2) offers an excellent observational capability for studying responses of vegetation to changes in land cover and land use. It will be possible to quantify the recovery of most land cover types following major disturbances such as clear cutting and fires. In addition, the mission's scientific objectives could easily be expanded to include important scientific issues related to biogeochemical processes and landscape spatial patterns (e.g., habitat fragmentation and biodiversity) that are not directly related to the carbon cycle. The ability to acquire coincident hyperspatial data is an especially critical requirement for these scientific applications. Accurate coregistration of the hyperspatial and coarser resolution data from this mission will be essential for these LCLUC objectives.

Hyperspectral Observations and Data Analysis

The potential for using hyperspectral image data (see TEB, section 2.3.2.2) to improve discrimination of vegetation types and species composition and to enable the identification and mapping of more land cover types than is now possible using multispectral data is of enormous appeal. The NMP EO-1 technology demonstration mission will provide the first opportunity to evaluate such applications from space. Sources of hyperspectral data beyond EO-1 depend very much on potential commercial and international satellite initiatives and the continued availability of airborne hyperspectral imagers.

2.3.3.3 Field Campaigns and Process Studies for Land Cover and Land Use Change

Field experiments and process studies are employed to improve parameterizations in ecosystem models that simulate land cover change. Field campaigns to validate satellite data products also will continue to be an integral part of the program. Airborne remote sensing, primarily to acquire hyperspatial and hyperspectral data, will be conducted to aid in the interpretation of satellite data within these campaigns. For the next few years, LCLUC research conducted as part of the LBA-Ecology and SAFARI 2000 campaigns (see TEB, section 2.3.2.3) will emphasize linking the spatial and temporal dynamics of land cover change with analysis of the determinants of land use change in the context of regional case studies.

NASA will conduct process studies focused on the human dimensions of land cover and land use change when they can be related to observed, recent changes in the landscape. Case studies focused on understanding the economic, social, and policy factors responsible for forest conversion, land use intensification, and forest degradation will be focused on regions undergoing rapid change, including the U.S., Amazonia, Central America, Southeast Asia, Southern and Central Africa, and Russia. By choosing representative regions and typical changes in land cover and land use, it is hoped that the knowledge gained in these case studies will be applicable to other parts of the world.

The ESE LCLUC program element will continue to support essential *in situ* observations within its field campaigns, case studies, and satellite data analysis and validation research projects. For example, converting rates of land cover change into changes in carbon fluxes currently requires *in situ* measurements of biomass. Results from the Landsat Pathfinder Humid Tropical Forest Project suggest that while Landsat can detect the occurrence of intensive selective logging, *in situ* observations are required to arrive at consistent and reproducible regional estimates of slow degradation and to quantify biomass loss. Similarly, the calculation of emissions from biomass burning and determination of atmospheric impacts will require empirical emission factors that can only be derived from *in situ* observations.

2.3.3.4 Modeling and Integration for Land Cover and Land Use Change

Process studies and satellite observations are insufficient to arrive at the desired quantitative information on the causes and consequences of land cover change. Models are necessary to integrate fundamental knowledge of the operative processes and current observations, to investigate approaches for spatial and temporal scaling (from individual farms to regions), to simulate land use change responses, to assess consequences, and to predict future changes.

Because existing ecosystem models do not utilize data sets of actual land cover or land use, and are limited by this constraint, a core objective for LCLUC research is to develop methods to incorporate land cover and land use information into existing biogeochemical and biophysical models. This research will be conducted in close cooperation with model development activities in the national and international community. Model intercomparisons, such have been conducted under the joint NASA/NSF/USFS/Electrical Power Research Institute (EPRI) VEMAP study and in cooperation with the IGBP Global Analysis, Interpretation and Modeling (GAIM) core project, will be continued to assess improved models incorporating land cover and land use change information. In particular, the LCLUC program element will support the development of regional-scale integrated assessment models that can be applied to the evaluation of the potential outcomes of different management practices and assessment of the consequences of policies that affect land cover conversion.

Predictive models of the Earth System need to account for past and present extent and intensity of human land modification, and for the possible changes in these practices in the future. Predicting changes at the global scale will be challenging, since human decision making at the local scale is one of the most important drivers. Projections, therefore, will carry uncertainties of a different kind, as compared to physical or biological models, reflecting socioeconomic constraints as well as non-monetary influences on land use systems. Improved data sets of past and present land use are of highest priority for advancing current models. Modeling within the LCLUC program element will endeavor to cooperate with and build linkages to those programs that can add information, modeling tools, and realistic scenarios on social, economic, and policy influences on future Earth system change. The objective is to begin the research needed to develop coupled socioeconomic and natural science models for predicting scenarios of change in land cover and land use and their consequences.

The LCLUC program element also will invest in the development, refinement, and implementation of algorithms and data analysis methods to advance its objective of generating periodic global inventories of land cover and land use change. Synergies will be encouraged with EOSDIS, ESIPs, NewDISS, and other ESE programs that are also developing remote sensing data analysis and information processing techniques. Emphasis will be given to encouraging cost-effective and efficient data management, analysis, and archiving systems and to making the LCLUC data sets easily accessible and affordable for the research community.

2.4 LINKAGES

Linkages with other NASA programs

Scientific findings about primary productivity and ecosystem response to environmental change are the foundation for a broad range of potential applications in agriculture, forestry, fisheries, and environmental monitoring. Coordination with the ESE Applications programs will be emphasized to develop new applications of EOS, Landsat 7, VCL, and other new data types. Research on land cover and land use change in support of national and international environmental vulnerability assessments also will be a priority. The study of ecosystem disturbances by fire, flooding, oil spills, and extreme weather events provides the fundamental underpinning of applied studies conducted under the Natural Hazards program element. In particular, joint research on the impacts of fires will continue to be a priority.

Research on terrestrial ecosystem and land cover interactions with the atmosphere requires strong scientific linkages with the Global Water and Energy Cycle research theme, in particular the Land Surface Processes and Hydrology program element (section 4.3.3), recognizing that water is essential for all life and that vegetation controls fluxes of water into the atmosphere. Likewise, there are important linkages between river discharges and their chemical composition and coastal marine ecosystems. Equally strong linkages exist with the Atmospheric Chemistry, Aerosols and Solar Radiation research theme (see Chapter 3) as regards sources and sinks of trace gases and particulate matter (section 6.2.2). Likewise, the fundamental connection between ocean biological and biogeochemical processes and the ocean circulation is an essential linkage with physical oceanography (Global Ocean Circulation and Sea-Ice element of the Ocean and Ice research theme; section 5.3.1). These internal linkages are manifested by joint involvement in cross-disciplinary projects, including field campaigns.

The ESE's research on the biology and biogeochemistry of ecosystems contributes to NASA's cross-Enterprise research program in Astrobiology. In particular, ESE leads research efforts aimed at the Astrobiology goal of "determining how ecosystems respond to environmental change on time scales relevant to human life on Earth". ESE also contributes to Astrobiology through research on microbiology (related to controls on nutrient cycling and trace gas emissions), the development of Earth system models that simulate the co-evolution and adaptation of life and the changing environment, and on developing understanding of the "signals of life" that can be remotely sensed for Earth.

Linkages with other US agencies

ESE research on the biology and biogeochemistry of ecosystems and the global carbon cycle will be conducted as part of a larger national program coordinated by the Subcommittee on Global Change Research (USGCRP) of the Committee on Environment and Natural Resources (CENR). ESE also coordinates with the CENR Subcommittee on Ecological Systems. NASA recognizes the importance of the National and Regional Assessment Program of USGCRP and contributes scientific information based on satellite data products and regional land use change case and field studies. NASA has been a participant of the multi-agency Terrestrial Ecology and Global Change (TECO) Program with the National Science Foundation (NSF), the Departments of Energy and Agriculture (DOE; USDA), the National Oceanic and Atmospheric Administration (NOAA), and the Environmental Protection Agency (EPA). NASA has co-sponsored the VEMAP terrestrial ecosystem model intercomparison program along with NSF, the US Forest Service, and EPRI. NASA is a participant in the DOE-led AmeriFlux network of towers that measure carbon dioxide fluxes. The incipient National Oceanographic Partnership Program is expected to provide an effective conduit for NASA participation in a number of research programs that encompass the mission of several agencies, notably the Ecology and Oceanography of Harmful Algal Blooms (ECOHAB) and the Research and Monitoring Program on Ecological Effects of Environmental Stressors Using Coastal Intensive Sites (CISNet).

International linkages

Significant international cooperative activities are conducted in connection with major field campaigns. The LBA field campaign (section 2.3.2.3) is led by Brazil and involves substantial cooperation, both among individual scientists from the U.S., Brazil, other Amazonian countries, and Europe, and between NASA and the Brazilian Institute for Space Research (INPE). The BOREAS campaign and follow-on research have been conducted jointly with several institutions in Canada. The SAFARI 2000 campaign now being planned will involve the active participation of South Africa and other African nations. NASA also works with Russia on AVHRR data acquisition and the analysis of the effects of fires and other disturbances on boreal forest productivity and carbon dynamics. The validation of EOS data products requires a worldwide network of test sites where *in situ* observations are made. NASA contributed to the selection of the sites, and has exercised leadership in coordinating a network of international carbon flux tower networks (FluxNet) and in organizing data and information exchanges.

Intercomparison and exploitation of satellite data sets constitute another focus for international cooperative activities. NASA is a sponsor of the International Ocean Color Coordinating Group (IOCCG), an affiliate organization of the international Scientific Committee on Oceanic Research, that provides a forum for the exchange of information and technical guidance on ocean color measurements between space agencies with current or planned ocean color satellite missions. As part of the SIMBIOS program, NASA co-sponsors validation cruises with other countries. In addition, NASA maintains or supports ocean moorings that provide basic optical validation data for all ocean color measurements. NASA is planning a significant contribution to the Global Observation of Forest Cover Project (under the International Global Observing Strategy (IGOS) Partnership and the Committee on Earth Observation Satellites (CEOS)). The goal of this project is to develop operational forest cover monitoring systems to serve the needs of the global change science community, forest managers, and policy makers. NASA is also a partner in the Global Rain and Boreal Forest Mapping Project led by Japan, based on the use of JERS-1 SAR data to map inundated wetlands in Amazonia and to classify tropical and boreal forest ecosystems globally.

The research agenda for NASA research on the biology and biogeochemistry of ecosystems and the global carbon cycle is heavily influenced by the scientific plans and initiatives of the International Geosphere-Biosphere Programme (IGBP) of the International Council of Scientific Unions. In particular, NASA supports the Global Change and Terrestrial Ecosystems (GCTE) Focus 1 project office and has developed regional land cover and land use science networks in Southeast Asia and Southern Africa (in partnership with the System for Analysis, Research, and Training in global change science (START) initiative of IGBP). Various land cover and land use research activities are implemented in conjunction with other international programs such as the U.S. AID Central Africa Project for the Environment (CARPE) and relevant host countries.

2.5 REFERENCES

IGBP, 1992: *Global Change and Terrestrial Ecosystems: The Operational Plan*; International Geosphere-Biosphere Programme, Stockholm, Sweden.

IGBP, 1997: *The Terrestrial Biosphere and Global Change: Implications for Natural and Managed Ecosystems*; International Geosphere-Biosphere Programme, Stockholm, Sweden.

IGBP/IHDP, 1995: *Land-Use and Land-Cover Change: Science/Research Plan*; International Geosphere-Biosphere Programme, Stockholm, Sweden, and International Human Dimensions Programme on Global Environmental Change, Geneva, Switzerland.

IPCC, 1996: *Climate Change 1995: The Science of Climate Change*; Cambridge University Press, Cambridge, United Kingdom.

Kennel, C., E. Frieman, B. Moore and L. Shaffer, 1999: *Report of the NASA Earth Science Enterprise Post-2002 Mission Planning Workshop, Easton, MD*; National Aeronautics and Space Administration, Washington, DC.

NASA, 1999: *EOS Science Plan: The State of Science in the EOS Program*; Goddard Space Flight Center, National Aeronautics and Space Administration, Greenbelt, MD

NRC, 1992: *Oceanography in the Next Decade*; National Research Council, Ocean Studies Board; National Academy Press, Washington, DC.

NRC, 1994: *The Role of Terrestrial Ecosystems in Global Change: A Plan for Action*; National Academy Press, Washington, DC.

NRC, 1999: *Global Environmental Change: Research Pathways for the Next Decade;* National Research Council, Committee on Global Change Research; National Academy Press, Washington, DC.

Sarmiento, J.L., S.C. Wofsy, E. Shea, A. S. Denning, W. Easterling, C. Field, I. Fung, R. Keeling, J. McCarthy, S. Pacala, W. M. Post, D. Schimel, E. Sundquist, P. Tans, R. Weiss, and J. Yoder, 1999: *A U.S. Carbon Cycle Science Plan*; University Corporation for Atmospheric Research, Boulder, Colorado.

USGCRP, 1999: *Our Changing Planet: The FY 2000 U.S. Global Change Research Program*; U.S. Global Change Research Program, Washington, DC.

WHOI, 1995: *The Ecology and Oceanography of Harmful Algal Blooms, a National Research Agenda*; Woods Hole Oceanographic Institution, Woods Hole, MA.